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(54) Title: SUBSTITUTED TETRAHYDROFURAN ANALOGS OF PROSTAGLANDINS AS OCULAR HYPOTENSIVES (57) Abstract Substituted tetrahydrofuran analogs of prostaglandins and methods of their use in treating glaucoma and ocular hypertension are disclosed.		

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**SUBSTITUTED TETRAHYDROFURAN ANALOGS
OF PROSTAGLANDINS AS OCULAR HYPOTENSIVES**

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Background of the Invention

The present invention relates to novel compounds and compositions, and methods of their use in the treatment of glaucoma and ocular hypertension. In particular, the present invention relates to the use of certain substituted tetrahydrofuran analogs of D and F series prostaglandins to treat glaucoma and ocular hypertension.

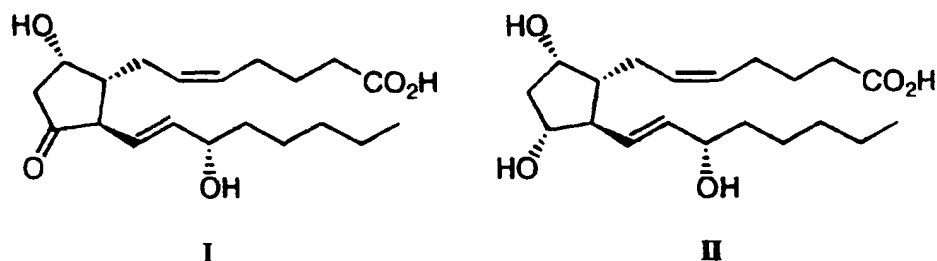
Glaucoma is a progressive disease which leads to optic nerve damage, and, ultimately, total loss of vision. The causes of this disease have been the subject of extensive studies for many years, but are still not fully understood. The principal symptom of and/or risk factor for the disease is elevated intraocular pressure or ocular hypertension due to excess aqueous humor in the anterior chamber of the eye.

The causes of aqueous humor accumulation in the anterior chamber are not fully understood. It is known that elevated intraocular pressure ("IOP") can be at least partially controlled by administering drugs which reduce either the production of aqueous humor within the eye, such as beta-blockers and carbonic anhydrase inhibitors, or increase the flow of aqueous humor out of the eye, such as miotics and sympathomimetics.

Most types of drugs conventionally used to treat glaucoma have potentially serious side effects. Miotics such as pilocarpine can cause blurring of vision and other visual side

effects, which may lead either to decreased patient compliance or to termination of therapy. Systemically administered carbonic anhydrase inhibitors can also cause serious side effects, such as nausea, dyspepsia, fatigue, and metabolic acidosis, which side effects can affect patient compliance and/or necessitate the termination of treatment. Moreover, some beta-blockers have increasingly become associated with serious pulmonary side effects attributable to their effects on beta-2 receptors in pulmonary tissue. Sympathomimetics may cause tachycardia, arrhythmia and hypertension. There is therefore a continuing need for therapies which control the elevated intraocular pressure associated with glaucoma.

Prostaglandins, which are metabolite derivatives of arachidonic acid, have recently been pursued for possible efficacy in lowering IOP. Arachidonic acid in the body is converted to prostaglandin G₂, which is subsequently converted to prostaglandin H₂. Other naturally occurring prostaglandins are derivatives of prostaglandin H₂. A number of different types of prostaglandins have been discovered including A, B, D, E, F, G, I and J-series prostaglandins (EP 0 561 073 A1). Of interest in the present invention are compounds which are believed to exhibit IOP lowering mechanisms similar to those exhibited by PGD₂ (formula (I)) and PGF_{2α} (formula (II)):



The relationship between prostaglandin DP receptor activation and IOP lowering effects is not well understood. Various publications have reported that DP receptor activation leads to second messenger activation and in particular, to the stimulation of adenylate cyclase and resultant increases in cAMP levels (Thierauch, *Prostaglandins and their Receptors: II. Receptor Structure and Signal Transduction*, Journal of Hypertension, volume 12, pages 1-5 (1994). Regardless of mechanism, PGD₂ has been shown to lower IOP (Nakajima, *Effects of Prostaglandin D₂ and its analog, BW245C, on Intraocular*

Pressure in Humans, Graefe's Archive Ophthalmology, volume 229, pages 411-413 (1991)). Thus, it has been of interest in the field to develop synthetic PGD₂ analogs with IOP lowering efficacy.

5 Synthetic PGD₂-type analogs have been pursued in the art (Graefe's Archive Ophthalmology, volume 229, pages 411-413 (1991)). Though some PGD₂-type molecules lower IOP, these types of molecules have also been associated with undesirable side effects resulting from topical ophthalmic dosing. Such effects have included an initial increase in IOP, conjunctival hyperemia, increases in microvascular permeability, and increases in
10 eosinophile infiltration (Alm, *The Potential of Prostaglandin Derivatives in Glaucoma Therapy*, Current Opinion in Ophthalmology, volume 4, No. 11, pages 44-50 (1993)).

Similarly, the relationship of prostaglandin FP receptor activation and IOP lowering effects is not well understood. It is believed that FP receptor activation leads to increased
15 outflow of aqueous humor. Regardless of mechanism, PGF_{2α} and some of its analogs have been shown to lower IOP (Giuffre, *The Effects of Prostaglandin F_{2α} the Human Eye*, Graefe's Archive Ophthalmology, volume 222, pages 139-141 (1985); and Kerstetter et al., *Prostaglandin F_{2α}-1-Isopropylester Lowers Intraocular Pressure Without Decreasing Aqueous Humor Flow*, American Journal of Ophthalmology, volume 105, pages 30-34
20 (1988)). Thus, it has been of interest in the field to develop synthetic PGF_{2α} analogs with IOP lowering efficacy.

Synthetic PGF_{2α}-type analogs have been pursued in the art (Graefe's Archive Ophthalmology, volume 229, pages 411-413 (1991)). Though PGF_{2α}-type molecules may
25 lower IOP, these types of molecules have also been associated with undesirable side effects resulting from topical ophthalmic dosing. Such effects include an initial increase in IOP, breakdown of the blood aqueous barrier and conjunctival hyperemia (Alm, *The Potential of Prostaglandin Derivatives in Glaucoma Therapy*, Current Opinion in Ophthalmology, volume 4, No. 11, pages 44-50 (1993)).

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Based on the foregoing, a need exists for the development of molecules that may activate the prostaglandin DP and/or FP receptors, yielding a more efficacious lowering of IOP, while exhibiting fewer or reduced side effects.

5 An agent which exhibits comparable or improved efficacy, but with reduced side effects when compared to other agents, is said to have an improved therapeutic profile. It is an object of this invention to provide a class of IOP lowering agents with an improved therapeutic profile over endogenous prostaglandins, and methods of their use.

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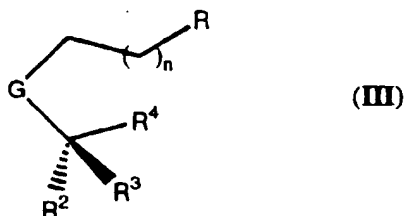
Summary of the Invention

The present invention is directed to compositions and methods of their use in treating glaucoma and ocular hypertension. In particular, the present invention provides
15 certain classes of substituted tetrahydrofurans which may possess functional DP and/or FP receptor agonist activity, and methods of their use in treating glaucoma and ocular hypertension.

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Detailed Description of the Invention

It has unexpectedly been found that substituted tetrahydrofurans of the present invention exhibit an improved therapeutic profile in the treatment of glaucoma and ocular hypertension when compared to natural prostaglandins and many of their known analogs.
25 The substituted tetrahydrofurans of the present invention are heptanoic acid derivatives having the following formula (III):



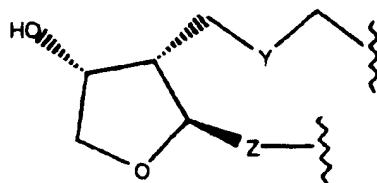
wherein:

R = pharmaceutically acceptable ester moiety, CO_2R^1 , CONR^7R^8 , CH_2OR^9 , or

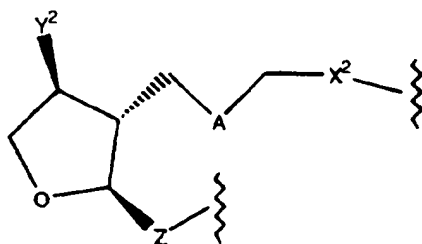
$\text{CH}_2\text{NR}^{10}\text{R}^{11}$, where $\text{R}^1 = \text{H}$ or cationic salt moiety; R^7 and R^8 are the same or different = H or alkyl; $\text{R}^9 = \text{H}$, acyl, or alkyl; and R^{10} and R^{11} are the same or different = H, acyl, or alkyl; with the proviso that if one of R^{10} and $\text{R}^{11} = \text{acyl}$, then the other = H or alkyl;

$n = 0$ or 2;

G is:

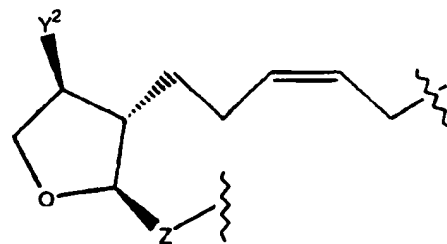


(i)



(ii)

or



(iii)

15

wherein:

$Y = \text{CH}_2\text{CH}=\text{CH}$ (*cis* olefin), $\text{CH}=\text{CHCH}_2$ (*cis* olefin), or $\text{CH}_2\text{CH}_2\text{CH}_2$;

$Z = \text{C}\equiv\text{C}$, *trans* $\text{CH}=\text{CH}$, or CH_2CH_2 ;

$Y^2 =$ halogen or alkoxy;

$X^2 = \text{O}$, S , or CH_2 ; and

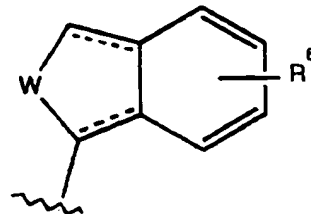
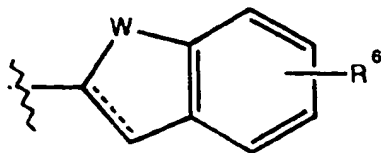
5 $A = \text{cis } \text{CH}=\text{CH}$, CH_2CH_2 , or $\text{C}\equiv\text{C}$;

one of R^2 and $R^3 = \text{H}$, and the other $= \text{F}$ or OH , where the OH may be free or functionally modified; or R^2 and R^3 taken together $= \text{OCH}_2\text{CH}_2\text{O}$ or double bonded O (carbonyl); and

10 $R^4 =$ cyclohexyl, linear or branched $\text{C}_5\text{-C}_7$ alkyl, or R^5 , wherein:

$R^5 = (\text{CH}_2)_m\text{Xphenyl}$ or $(\text{CH}_2)_p Z^2$, where $\text{X} = \text{O}$ or CH_2 ; $m = 1\text{-}6$; the phenyl is either unsubstituted or substituted with R^6 , where $R^6 =$ halogen, CH_3 , CF_3 , CN , OCH_3 or acetyl; $p = 0\text{-}6$; and

15 $Z^2 =$



or

wherein:

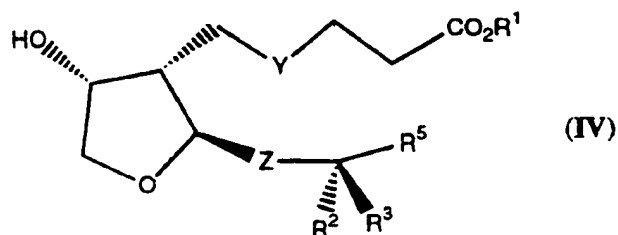
20 $W = \text{O}$, CH_2 , CH_2CH_2 , or $\text{CH}=\text{CH}$; and R^6 is as defined above;

provided that when G is (i) then $R^4 = R^5$; and when G is (ii) or (iii) then $R^4 =$ cyclohexyl, linear or branched $\text{C}_5\text{-C}_7$ alkyl, and R^2 , R^3 are different $= \text{H}$ and OH .

25 For purposes of the foregoing and following definitions, the term "pharmaceutically acceptable ester moiety" means any ester moiety that would be suitable for therapeutic administration to a patient by any conventional means without significant deleterious health

consequences. Similarly, the term "ophthalmically acceptable ester moiety" means any pharmaceutically acceptable ester moiety that would be suitable for ophthalmic application, i.e. non-toxic and non-irritating. Preferred are ophthalmically acceptable esters such as alkyl and alkylcycloalkyl esters of carboxylic acids. Most preferred are C₂-C₅ alkyl esters of carboxylic acids, and especially isopropyl esters.

Preferred compounds of the present invention are those of formula IV:



10

wherein:

R^1 = H, or C₂-C₅ linear or branched alkyl;

Y = CH₂CH=CH (*cis* olefin), CH=CHCH₂ (*cis* olefin), or CH₂CH₂CH₂;

Z = C≡C, *trans* CH=CH, or CH₂CH₂;

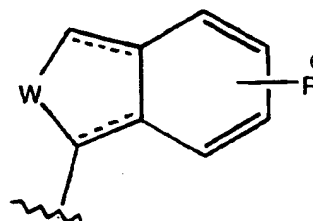
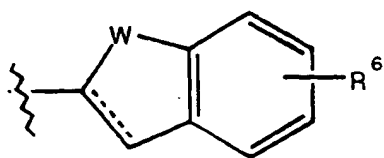
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one of R^2 and R^3 = H, and the other = F or OH, where the OH may be free or functionally modified; or R^2 and R^3 taken together = OCH₂CH₂O or double bonded O (carbonyl); and

R^5 = (CH₂)_mXphenyl or (CH₂)_pZ², where X = O or CH₂; m = 1-6; the phenyl is either unsubstituted or substituted with R^6 , where R^6 = halogen, CH₃, CF₃, CN, OCH₃ or acetyl; p = 0-6; and

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Z^2 =

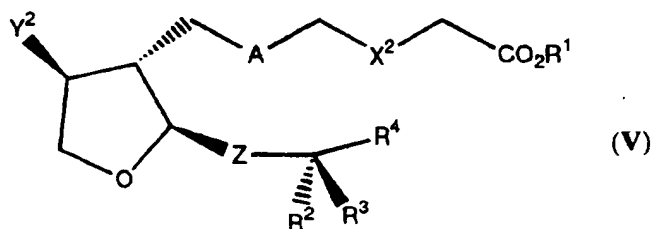


or

wherein:

W = O, CH₂, CH₂CH₂, or CH=CH; and R⁶ is as defined above.

5 Other preferred compounds of this invention include those of formula V:



wherein:

R¹ = H or C₂-C₅ linear or branched alkyl;

10 X² = O, or CH₂;

A = *cis* CH=CH, CH₂CH₂, or C≡C ;

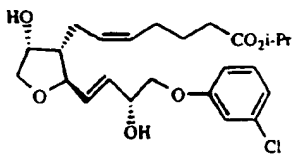
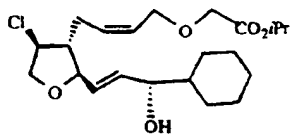
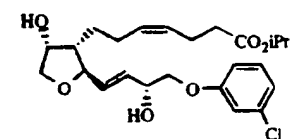
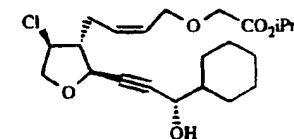
Y² = halogen;

Z = C≡C, *trans* CH=CH, or CH₂CH₂;

R², R³ are different = H, and OH; and

15 R⁴ = cyclohexyl, or C₅-C₇ linear or branched alkyl.

Especially preferred compounds of this invention are:

Compound Number	Compound Name	Compound Structure
VI	Isopropyl [2 <i>R</i> (1 <i>E</i> ,3 <i>R</i>),3 <i>S</i> (5 <i>Z</i>),4 <i>R</i>]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-hydroxy-3-furanyl]-5-heptenoate.	
VII	Isopropyl [2 <i>R</i> (1 <i>E</i> ,3 <i>S</i>),3 <i>R</i> (5 <i>Z</i>),4 <i>S</i>]-7-[Tetrahydro-4-chloro-2-(3-cyclohexyl-3-hydroxy-1-propenyl)-3-furanyl]-3-oxa-5-heptenoate.	
VIII	Isopropyl [2 <i>R</i> (1 <i>E</i> ,3 <i>R</i>),3 <i>S</i> (4 <i>Z</i>),4 <i>R</i>]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-hydroxy-3-furanyl]-4-heptenoate.	
IX	Isopropyl [2 <i>S</i> (3 <i>S</i>),3 <i>R</i> (5 <i>Z</i>),4 <i>S</i>]-7-[Tetrahydro-4-chloro-2-(3-cyclohexyl-3-hydroxy-1-propynyl)-3-furanyl]-3-oxa-5-heptenoate.	

The PGD₂ type analogs of the present invention (i.e. Compound III, wherein G is (ii) or (iii)) are believed to be novel.

With the exception of: methyl (5Z,13E,15R)-9 α -acetoxy-15-hydroxy-17-(3-trifluoromethylphenyl)-11-oxa-18,19,20-trinorprosta-5,13-dienoate and methyl
5 (5Z,13E,15S)-9 α -acetoxy-15-hydroxy-17-(3-trifluoromethylphenyl)-11-oxa-18,19,20-trinorprosta-5,13-dienoate, syntheses of which have been reported by Verdoorn, et al., S. African J. Chem., 40:134-138 (1987), the PGF_{2 α} -type analogs useful in the present invention (i.e. Compound III, wherein G is (i)) are also believed to be novel. Related 11-oxa PGFs outside the scope of the present invention are, however, known and their
10 syntheses are described in the literature. The 11-oxa analogs of PGF_{2 α} and PGF_{2 β} are disclosed in Hanessian, et al., Carbohydrate Research, 141:221-238 (1985); and Thiem et al., Liebigs Ann. Chem., 2151-2164 (1985). Arndt, et al., S. African J. Chem., 34:121-127 (1981), and U.S. Patent No. 4,133,817, similarly disclose 11-oxa analogs of PGF_{2 α} . The entire contents of these references are hereby incorporated herein.

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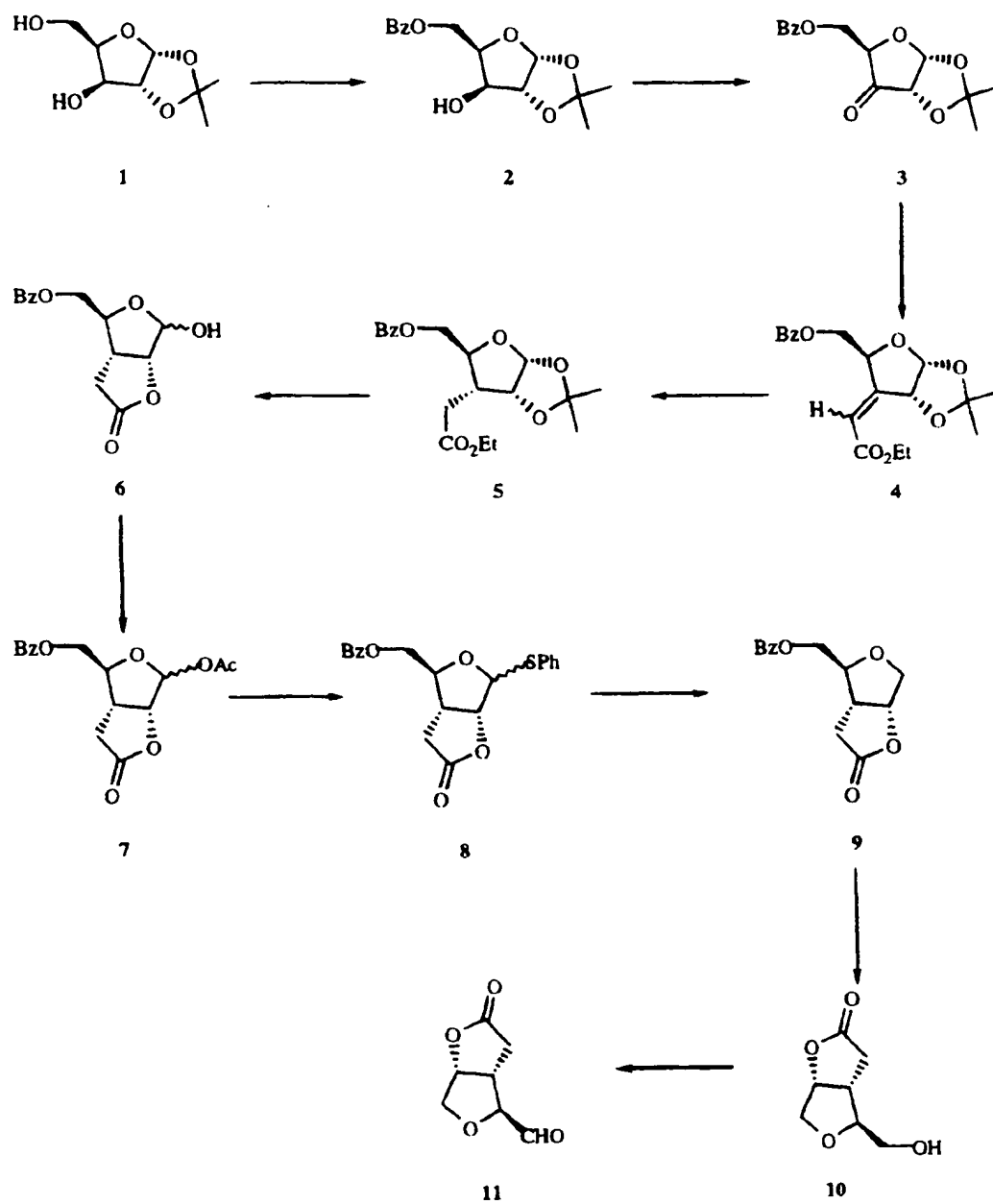
In the foregoing illustrations, as well as those provided hereinafter, wavy line attachments indicate that the configuration may be either alpha (α) or beta (β). The dashed lines on bonds between carbons, e.g. in the bicyclic structural formula for Z², indicate a single or double bond. Two solid lines present between carbons specify the configuration
20 of the relevant double bond. Hatched lines indicate the α configuration, and a solid triangular line indicates the β configuration.

In the following Examples 1-8, the following standard abbreviations are used: g = grams (mg = milligrams); mol = moles (mmol = millimoles); mL = milliliters; mm Hg =
25 millimeters of mercury; mp = melting point; bp = boiling point; h = hours; and min = minutes. In addition, "NMR" refers to nuclear magnetic resonance spectroscopy and "MS" refers to mass spectrometry.

**EXAMPLE 1: SYNTHESIS OF (3aR, 4S, 6aR)-Hexahydro-2-ox furo-
[3,4-b]furan-4-carboxaldehyde (11).**

The compounds of this invention (both the PGD₂-type and the PGF_{2α}-type analogs)
5 may be prepared from the same intermediate compound, (3aR, 4S, 6aR)-hexahydro-2-oxofuro[3,4-b]furan-4-carboxaldehyde (11) which is prepared from the readily available 1,2-*O*-isopropylidene- α -D-xylofuranose (1) according to published methodology (Arndt, et al. S. Afr. J. Chem., 34:121-127 (1981); U.S. Patent No. 4,133,948). The following Scheme 1 outlines the synthetic route to (11).

Scheme 1: Synthesis of Aldehyde 11



A:5-O-Benzoyl-1,2-O-isopropylidene- α -D-xylofuranose (2):

A solution of 1,2-O-isopropylidene- α -D-xylofuranose **1** (30 g, 0.15 mol) in 360 mL of CH₂Cl₂ was cooled to 0 °C and to it was added 20 mL (0.23 mol) of pyridine and a catalytic amount (1.0 g) of *N,N*-dimethylaminopyridine. The resulting mixture was stirred at 0 °C for 10 min, at which time 20 mL (0.17 mol) benzoyl chloride was added to it dropwise over a period of 30 min. The reaction mixture was stirred at 0 °C for an additional 30 min and then quenched by the addition of 200 mL a saturated solution of NH₄Cl. The reaction was allowed to warm to room temperature, the layers were separated, and the aqueous layer was extracted with 3 X 50 mL of CH₂Cl₂. The combined organic extracts were washed with 3 X 50 mL of a 10% aqueous solution of CuSO₄, 2 X 50 mL of water and brine. The organic solution was dried over anhydrous MgSO₄, filtered and concentrated. The crude product mixture was purified by chromatography on silica gel to afford 44.3 g (95% yield) of **2** as a colorless liquid: *R*_f 0.54 (60% EtOAc/hexane); ¹H-NMR (CDCl₃) δ 8.03 (m, 2H), 7.40-7.68 (m, 3H), 5.97 (d, 1H, *J* = 3.6 Hz), 4.80 (m, 1H), 4.61 (d, 1H, *J* = 3.4 Hz), 4.37 (m, 2H), 4.20 (s, broad, 1H), 3.35 (broad, 1H), 1.50 (s, 3H), 1.32 (s, 3H).

B:5-O-Benzoyl-1,2-O-isopropylidene- α -D-erythropentofuranos-3-ulose (3):

20

A solution of oxalyl chloride (2.0 M in CH₂Cl₂, 113 mL, 0.22 mol) in 400 mL of anhydrous CH₂Cl₂ was cooled to -78 °C under a N₂ atmosphere. To this, a solution of dimethylsulfoxide (32 mL, 0.45 mol) in 50 mL of anhydrous CH₂Cl₂ was added dropwise over a period of 5 min. After the resulting solution had been stirred at the same temperature for 5 min, a solution of **2** (44.3 g, 0.15 mol) in 500 mL of anhydrous CH₂Cl₂ was added to it dropwise over a period of 15 min. Stirring was continued at -78 °C for an additional 15 min. Triethylamine (60 mL, 0.42 mol) was then added to the reaction mixture, and after a further 15 min at -78 °C the cold temperature bath was removed, and the stirring was continued for 10 min. The reaction was then quenched by the addition of 400 mL of water. The biphasic mixture was allowed to warm to room temperature and the layers were separated. The aqueous layer was extracted with 3 X 100 mL of CH₂Cl₂. The

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organic extracts were combined and washed with water (3 X 100 mL) and brine and was dried over anhydrous Na₂SO₄. Filtration and solvent removal afforded crude **3** (42.5 g, 96% yield) as a pale yellow solid, which was used in the next step without further purification: ¹H-NMR (CDCl₃) δ 7.97 (m, 2H), 7.40 - 7.65 (m, 3H), 6.14 (d, 1H, *J* = 4.40 Hz), 4.69 (m, 2H), 4.44 (m, 2H), 1.15 (s, 3H), 1.43 (s, 3H).

C:(3aR, 4S, 6RS, 6aR)-4-(Benzoyloxy)methylhexahydro-6-hydroxyfuro[3,4-b]furan-2-one (6):

The crude sample of **3** (42.5 g, 0.15 mol), triethylphosphonoacetate (40.5 g, 0.18 mol) and lithium chloride (7.6 g, 0.18 mol) were combined and dissolved in 1.0 L of anhydrous THF. The solution was cooled to 0 °C and to it triethylamine (25.3 mL, 0.18 mol) was added dropwise. The resulting slurry was allowed to warm to room temperature gradually, and stirred under a N₂ atmosphere for 24 h. The reaction mixture was then poured into 500 mL of a 50% aqueous NaCl solution. The layers were separated and the aqueous layer was extracted with 2 X 200 mL of EtOAc. The combined organic extracts were dried over anhydrous MgSO₄. Filtration and solvent removal afforded 50 g of the crude enoate **4** as a mixture of two diastereomers which was used in the next step: *R_f* 0.58 and 0.50 (minor and major isomers, respectively, 50% EtOAc/hexane).

To a suspension of 30 - 40 g of Raney-Ni (Aldrich, washed to neutrality with distilled water) in 750 mL of methanol the crude enoate **4** (50 g) from above was added, and the resulting mixture was hydrogenated at 65-70 psi, at room temperature in a Parr high-pressure reactor for 18 h. The reaction mixture was carefully filtered through a pad of celite. The solids were washed thoroughly with methanol. The filtrates were combined and evaporated, and the crude product mixture was purified by passage through a short pad of silica gel to afford 46.7 g (85% yield for two steps) of **5** as a colorless liquid. This material was carried onto the next step: *R_f* 0.46 (50 % EtOAc/hexane): ¹H NMR (CDCl₃) δ 8.03 (m, 2H), 7.40 - 7.65 (m, 3H), 5.88 (d, *J* = 3.6 Hz, 1H), 4.85 (m, 1H), 4.05 - 4.65 (m, 5H), 2.78 (m, 1H), 2.40 (m, 2H), 1.52 (s, 3H), 1.32 (s, 3H), 1.25 (t, *J* = 7.15 Hz, 3H).

The acetonide **5** (46.7 g, 0.12 mol) obtained above was dissolved in 250 mL of a 4:1 mixture of glacial acetic acid and water, and the resulting solution was heated at 100 °C for 3.5 h. The reaction mixture was cooled to room temperature and the solvent was removed *in vacuo*. The residue was dissolved in 100 mL of toluene and the solution was concentrated to afford 39.6 g (quantitative yield) of **6** as pale yellow viscous liquid: R_f 0.23 (50% EtOAc/hexane); $^1\text{H-NMR}$ (CDCl_3) δ 8.01 (m, 2H), 7.38 - 7.69 (m, 3H), 5.62 (s, 1H), 4.93 (d, 1H, $J = 6.02$ Hz), 4.30 - 4.70 (m, 3H), 3.20 (m, 1H), 2.50 - 3.05 (m, 2H).

D:(3aR, 4S, 6RS, 6aR)-6-Acetyloxy-4-(benzoyloxy)methylhexahydrofuro[3,4-b]furan-2-one (7):

The lactone **6** (39.6 g, 0.14 mol) was dissolved in 70 mL of pyridine. To this solution 70 mL of acetic anhydride was added and the resulting mixture was stirred at room temperature for 20 h. The solvent was then evaporated and the residue was dissolved in 1.5 L of EtOAc. This solution was sequentially washed with 2 X 150 mL of water, 3 X 150 mL of a 0.25 N HCl solution water, 1 X 150 mL water and 1 X 100 mL brine. The organic layer was dried over anhydrous MgSO_4 , filtered and concentrated. The crude product was isolated as a yellow solid which was titrated with hot ether to afford 29.0 g of a white crystalline solid which was found to be a single diastereomer of the acetate by $^1\text{H-NMR}$. The mother liquor was concentrated and purified by chromatography on silica gel to afford 6.7 g of a mixture of diastereomeric acetates as a yellow liquid. The combined yield of **7** being 87%: R_f 0.3 (60 % EtOAc/hexane); $^1\text{H-NMR}$ (CDCl_3) δ (for major isomer only) 8.03 (m, 2H), 7.42 - 7.68 (m, 3H), 6.41 (s, 1H), 5.01 (d, 1H, $J = 6.3$ Hz), 4.45 (s, broad, 3H), 3.22 (m, 1H), 2.90 (dd, 1H, $J = 14.4, 9.0$ Hz), 2.62 (dd, 1H, $J = 14.4, 3.4$ Hz), 2.03 (s, 3H).

E:(3aR, 4S, 6RS, 6aR)-4-(Benzoyloxy)methylhexahydro-6-phenylthiofuro[3,4-b]furan-2-one (8):

To a suspension of **7** (35.7 g, 0.11 mol) and thiophenol (14.8 mL, 0.13 mol) in 220 mL of a 4:1 mixture of anhydrous toluene and dichloromethane at room temperature, boron

trifluoride etherate (6.9 mL, 0.05 mol) was added dropwise. The resulting mixture was stirred at the same temperature for 6.5 h and then carefully poured into a biphasic mixture of 1000 mL of EtOAc and 100 mL of a saturated aqueous solution of NaHCO₃ (sat. NaHCO₃). The layers were separated and the organic layer was washed with 2 X 100 mL of saturated NaHCO₃, 100 mL of water and 100 mL of brine. The organic layer was dried over anhydrous MgSO₄, filtered and concentrated to afford a yellow liquid. This material was dissolved in 50 mL of CHCl₃, and to it was added 200 mL of ether and 50 mL of hexane. The resulting solution was briefly cooled to -78 °C to induce crystallization. White powdery solid formed which was filtered off and washed with cold ether to afford 29.6 g of **8** (72 % yield) as a mixture of two diastereomers: R_f 0.70 and 0.53 (minor and major isomers, respectively, 60% EtOAc/hexane); ¹H-NMR (CDCl₃) δ (for major isomer only) 8.01 (m, 2H), 7.42 - 7.70 (m, 5H), 7.27 (m, 3H), 5.89 (d, 1H, J = 5.2 Hz), 5.29 (dd, 1H, J = 7.7, 5.2 Hz), 4.55 (m, 2H), 4.48 (m, 1H), 2.60 - 3.12 (m, 3H).

F:(3aR, 4S, 6aR)-4-(Benzoyloxy)methylhexahydrofuro[3,4-b]furan-2-one (9):

A 3-neck, 1000 mL round-bottom flask, equipped for overhead mechanical stirring, was charged with 29.6 g of **8** (80 mmol), 500 mL of ethanol and approximately 30 g of Raney-Ni (Aldrich, which had been washed to neutrality with distilled water). The resulting slurry was heated at reflux for 5 h while stirring vigorously. The reaction mixture was then cooled to room temperature, and the solids were carefully filtered off through a pad of celite. The residue was washed thoroughly with ethanol, and the combined filtrates were concentrated to afford a yellow solid which was purified by chromatography on silica gel to afford 7.63 g (36 % yield) of **9** as a white solid. A small sample was recrystallized from acetone/hexane to afford colorless needles: mp 89.5-90.0 °C; [α]_D²² +3.18 (c = 0.8 in CHCl₃); R_f 0.36 (60% EtOAc/hexane); ¹H-NMR (CDCl₃) δ 8.01 (m, 2H), 7.40 - 7.65 (m, 3H), 5.15 (m, 1H), 4.41 (m, 2H), 4.05 - 4.32 (m, 3H), 2.80 - 3.05 (m, 2H), 2.56 (d, 1H, J = 15.7 Hz); MS m/z at 263 for (M + H)⁺.

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G:(3aR, 4S, 6aR)-Hexahydro-2-oxofuro[3,4-b]furan-4-carboxaldehyde (11):

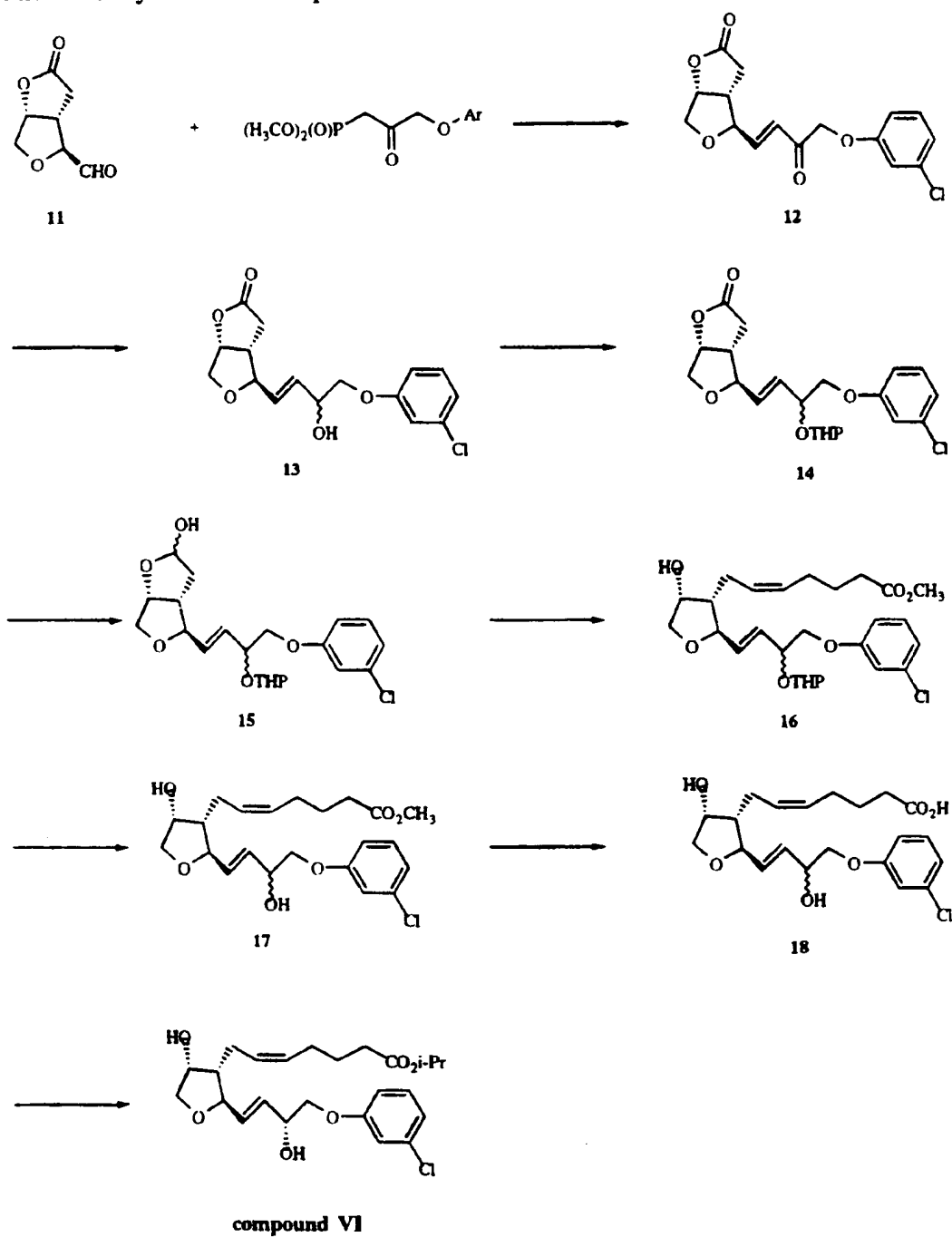
To a solution of the benzoate **9** (2.63 g, 10.0 mmol) in 50 mL of warm methanol was added 1.4 g (10.0 mmol) of solid K₂CO₃. The resulting slurry was stirred at room temperature for 2.5 h, at which time 150 mL of water was added and the mixture was treated with Amberlyst-15 (purified and activated) until the solution was at pH 2-3. The resin was filtered and washed with 50 mL of water, and the filtrates were combined and concentrated to approximately 200 mL. This solution was extracted with 3X50 mL of EtOAc, the organic extracts were discarded and the aqueous phase was evaporated *in vacuo*. The residue was taken up in 50 mL of toluene and the solvent was evaporated; this drying procedure was repeated twice. The product hydroxylactone **10** thus obtained (1.64 g, 95 % yield) was isolated as a pale yellow liquid. This material was used without further purification: ¹H-NMR (d₆-DMSO) δ (crude sample) 5.12 (m, 1H), 4.81 (t, 1H, J = 5.6 Hz, OH), 3.98 (dd, 1H, J = 10.3, 4.1 Hz), 3.85 (d, 1H, J = 10.5 Hz), 3.75 (m, 1H), 3.44 (m, 2H), 2.85 (m, 2H), 2.48 (m, 1H).

A solution of oxalyl chloride (2.0 M in CH₂Cl₂, 5.4 mL, 10.8 mmol) in 25 mL anhydrous CH₂Cl₂ was cooled to -78 °C under a N₂ atmosphere. To this, a solution of DMSO (1.5 mL, 21.6 mmol) in 5.0 mL of CH₂Cl₂ was added dropwise. The resulting mixture was stirred for 5 min, and then a solution of the hydroxylactone **10** obtained above (1.14 g, 7.21 mmol) in 50 mL of anhydrous CH₂Cl₂ was added dropwise. After 15 min at -78 °C, triethylamine (2.85 mL, 20.2 mmol) was added to the reaction and stirring was continued for an additional 15 min at -78 °C. The reaction was then allowed to warm to room temperature and filtered through a pad of celite. The filter cake was washed with CH₂Cl₂, the filtrates were combined and concentrated to approximately 10 mL; this solution was applied to a column of silica gel for chromatographic purification. The aldehyde **11** (0.9 g, 80 % yield) was isolated as a colorless liquid: R_f 0.6 (acetone); ¹H-NMR (CDCl₃) δ 9.71 (s, 1H), 5.10 (m, 1H), 4.24 (m, 1H), 3.65 - 3.89 (m, 2H), 2.96 (m, 1H), 2.64 (m, 1H), 1.85 (m, 1H).

**EXAMPLE 2: SYNTHESIS OF Isopropyl [2*R*(1*E*,3*R*),3*S*(5*Z*),4*R*]-7-
[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-
hydroxy-3-furanyl]-5-heptenoate (VI)**

- 5 Compound VI may be prepared according to the method described by the following Scheme 2.

Scheme 2: Synthesis of Compound VI:



A:[3aR, 4R(1E), 6aR]-4-[4-(3-Chlorophenoxy)-3-oxo-1-butenyl]hexahydrofuro[3,4-b]-furan-2-one (12):

A solution of dimethyl-3-(3-chlorophenoxy)-2-oxopropylphosphonate (2.34 g, 8 mmol) and LiCl (0.29 g, 6.9 mmol) in 15 mL of anhydrous THF was cooled to 0 °C under N₂ atmosphere and to it triethylamine (0.97 mL, 6.9 mmol) was added dropwise. A white slurry formed, which was stirred for 3 min at 0 °C, at which time a solution of the aldehyde **11** (0.9g, 5.76 mmol) in 15 mL of anhydrous THF was added to it. The resulting mixture was stirred at 0 °C for 1 h, and then partitioned between 100 mL of water and 250 mL of EtOAc. The layers were separated and the organic phase was washed with water and brine, and dried (MgSO₄). Filtration and solvent removal afforded a yellow liquid which was purified by chromatography on silica gel to yield 1.13 g of the enone **12** (60% yield) as a colorless, viscous liquid: R_f 0.29 (60 % EtOAc/hexane); ¹H-NMR (CDCl₃) δ 7.22 (m, 1H), 6.85 - 7.08 (m, 3H), 6.79 (m, 1H), 6.65 (dd, 1H, J = 16.2, 1.6 Hz), 5.10 (m, 1H), 4.69 (s, 2H), 4.38 (m, 1H), 4.10 (m, 2H), 2.88 (m, 2H), 2.57 (m, 1H).

B:[3aR, 4R(1E,3RS), 6aR]-4-[4-(3-Chlorophenoxy)-3-hydroxy-1-butenyl]hexahydrofuro[3,4-b]furan-2-one (13):

A mixture of **12** (1.0 g, 3.10 mmol) and CeCl₃·7H₂O (2.3 g, 6.2 mmol) was taken up in a mixture of CH₃OH (25 mL) and CHCl₃ (10 mL), and the solution was cooled to 0 °C. To this cold solution NaBH₄ (0.23 g, 6.2 mmol) was added in small portions over a period of 5 min. (CAUTION: vigorous hydrogen gas evolution occurs). The resulting mixture was stirred for an additional 3 min at 0 °C, and then poured into 100 mL of 0.5 N HCl solution. The aqueous solution was extracted with 3 X 50 mL of CHCl₃. The organic extracts were combined and washed with 3 X 50 mL of water and brine, and dried over anhydrous MgSO₄. Filtration and solvent removal afforded an oil which was purified by silica gel chromatography to give 0.71 g (70% yield) of **13** (a diastereomeric mixture of alcohols) as a colorless liquid: R_f 0.14 (60% EtOAc/hexanes); ¹H-NMR (CDCl₃) δ 7.21 (m, 1H), 6.95 (m, 2H), 6.78 (m, 1H), 5.89 (s, broad, 2H), 5.11 (m, 1H), 4.56 (m, 1H), 4.20 (m, 2H), 4.01 (m, 2H), 3.89 (m, 1H), 2.85 (m, 2H), 2.57 (m, 2H); ¹³C-NMR (CDCl₃) δ 175.62

(C=O), 158.96 (O-Ar), 134.93 (Cl-Ar), 130.95 and 130.80 (CH), 130.33 (CH), 129.86 and 129.75 (CH), 121.55 (CH), 115.02 (CH), 113.00 (CH), 84.57 and 84.51 (CH), 84.07 (CH), 72.48 (CH₂), 71.68 (CH₂), 69.82 and 69.76 (CH), 44.80 (CH), 32.49 (CH₂).

5 **C:[3aR, 4R(1E,3RS), 6aR]-4-[4-(3-Chlorophenoxy)-3-(tetrahydropyran-2-yl)oxy-1-butenyl]-hexahydrofuro[3,4-b]furan-2-one (14):**

A solution of **13** (0.71 g, 2.19 mmol) in 20 mL of CH₂Cl₂ was cooled to 0 °C. To this 0.5 mL (4.38 mmol) of 3,4-dihydro-2H-pyran was added followed by a catalytic
10 amount of *p*-toluenesulfonic acid (10 mg). The reaction was stirred at 0 °C for 15 min and then quenched by the addition of 10 mL of a saturated aqueous solution of NaHCO₃. The layers were separated and the aqueous layer was extracted with 2 X 10 mL of dichloromethane. The combined organic extracts were dried (MgSO₄), filtered and concentrated. The product **14** (0.78 g, 91% yield) was isolated as a colorless liquid after
15 chromatography of the crude on silica gel: R_f 0.28 (60% EtOAc/hexane).

D:Methyl [2R(1E,3RS), 3S(5Z), 4R]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-(tetrahydropyran-2-yl)oxy-1-butenyl]-4-hydroxy-3-furanyl]-5-heptenoate (16):

20 A solution of the lactone **14** (0.78 g, 1.9 mmol) in 20 mL of anhydrous THF was cooled to -78 °C under a N₂ atmosphere, and diisobutylaluminum hydride (DIBAL-H, 1.9 mL, 1.5 M in toluene, 2.8 mmol) was added to it dropwise. The resulting mixture was stirred at -78 °C for 1.5 h and then quenched at the same temperature by the careful addition of 5 mL of methanol. The mixture was allowed to warm to room temperature,
25 diluted with 50 mL of EtOAc and treated with 100 mL of a saturated, aqueous potassium sodium tartrate solution, with vigorous stirring, for 1 h. The layers were separated and the aqueous layer was extracted with 3 X 10 mL of EtOAc. The combined organic extracts were dried (MgSO₄), filtered and concentrated. The crude product thus obtained was purified by passage through a short pad of silica gel to afford the intermediate lactol **15**
30 (0.68 g, 87 % yield) as a colorless liquid: R_f 0.15 (60% EtOAc/hexane).

To a suspension of (4-carboxybutyl)triphenylphosphonium bromide (2.2 g, 4.9 mmol) in 20 mL anhydrous THF at 0 °C, potassium *tert*-butoxide (*t*-BuOK, 10.0 mL, 1.0 M THF, 10.0 mmol) was added dropwise and the mixture was stirred at 0 °C for 30 min. A solution of the lactol 15 obtained above (0.68 g, 1.65 mmol) in 50 mL of THF was then added to it dropwise. The resulting mixture was allowed to warm to room temperature and was stirred at that temperature for 16 h. The reaction was quenched by pouring it into a saturated aqueous solution of ammonium chloride (50 mL) which had been acidified to pH 2-3 with dilute aqueous HCl solution. The mixture was extracted with EtOAc (5 X 25 mL), and the combined organic extracts were washed with water (1 X 25 mL) and brine (1 X 25 mL) and dried over anhydrous Na₂SO₄. The solution was filtered, concentrated to approximately 10 mL and then cooled to 0 °C. This solution was treated with an excess of ethereal diazomethane at 0 °C. The excess diazomethane was evaporated off by bubbling N₂ through the solution for 1 h. The resulting pale yellow solution was concentrated and applied to a column of silica gel for purification by chromatography. The methyl ester 16 (0.38 g, 50 % yield, mixture of diastereomers) was isolated as a colorless liquid: R_f 0.27 (60% EtOAc/hexane).

E:Methyl [2R(1E,3RS), 3S(5Z), 4R]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-hydroxy-3-furanyl]-5-heptenoate (17):

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The compound 16 (0.37 g, 0.74 mmol) was dissolved in a mixture of 10 mL of methanol and 0.5 mL of water. The solution was cooled to 0 °C and to it was added about 10 drops of 12 N HCl. The resulting mixture was stirred at 0 °C for 15 min and then at room temperature for 45 min, at which time the reaction was quenched with solid NaHCO₃ (0.2 g). The mixture was transferred to a separatory funnel containing 25 mL each of CHCl₃ and saturated aqueous solution of NaHCO₃. The layers were separated and the aqueous layer was extracted with 4 X 25 mL of CHCl₃. The combined organic extracts were dried (Na₂SO₄), filtered and concentrated. The crude was purified by chromatography on silica gel to afford the diol 17 (0.28 g, 88% yield, mixture of diastereomers) as a colorless liquid: R_f 0.18 (80% EtOAc/hexane); ¹H-NMR (CDCl₃) δ 7.20 (m, 2H), 6.80 - 6.92 (m, 3H), 5.87 (m, 2H), 5.45 (m, 2H), 4.58 (m, 1H), 4.35 (m,

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1H), 3.80 - 4.20 (m, 6H), 3.66 (s, 3H), 2.22 - 2.60 (m, 4H), 2.15 (m, 4H), 1.69 (m, 2H);
MS *m/z* at 447 for (M+Na)⁺.

F: Isopropyl [2*R*(1*E*,3*R*), 3*S*(5*Z*), 4*R*]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-hydroxy-3-furanyl]-5-heptenoate (VI):

The diastereomeric mixture of methyl esters **17** (0.28 g, 0.65 mmol) was dissolved in 20 mL of methanol containing 2 mL of water. To this solution 0.2 g (4.76 mmol) of LiOH was added and the resulting mixture was stirred at room temperature for 5.5 h. The reaction mixture was then transferred to a separatory funnel containing 50 mL of CHCl₃ and 25 mL of a 1*N* aqueous HCl solution; the layers were separated and the aqueous phase was extracted with 4 X 25 mL portions of CHCl₃. The organic extracts were combined and washed with 3 X 10 mL of water and 1 X 25 mL of brine and dried over anhydrous Na₂SO₄. The solution was filtered, concentrated and purified by HPLC (RP-18, acetonitrile/water/TFA) to afford **18** (0.25 g, 93 % yield, diastereomeric mixture) as a clear colorless liquid: ¹H-NMR (CDCl₃) δ 7.22 (m, 2H), 6.85 - 7.05 (m, 3H), 5.86 (m, 2H), 5.44 (m, 2H), 4.84 (broad, 2H), 4.61 (m, 1H), 4.37 (m, 1H), 3.86 - 4.20 (m, broad, 6H), 2.00 - 2.65 (m, 6H), 1.50 - 1.95 (m, 3H); ¹³C-NMR (CDCl₃) δ 177.58 (C=O), 159.08 (O-Ar), 134.89 (Cl-Ar), 133.22 (CH), 132.46 (CH), 130.28, 129.84 (CH), 128.01 (CH), 121.43 (CH), 115.13, 115.10 (CH), 113.02 (CH), 82.26, 82.03 (CH), 75.54, 75.48 (CH₂), 72.58, 72.50 (CH), 71.59, 71.55 (CH₂), 70.48, 70.03 (CH), 51.39, 51.34 (CH), 32.68 (CH₂), 26.19 (CH₂), 24.41, 24.30 (CH₂), 22.33, 22.18 (CH₂); MS *m/z* at 433 for (M+Na)⁺.

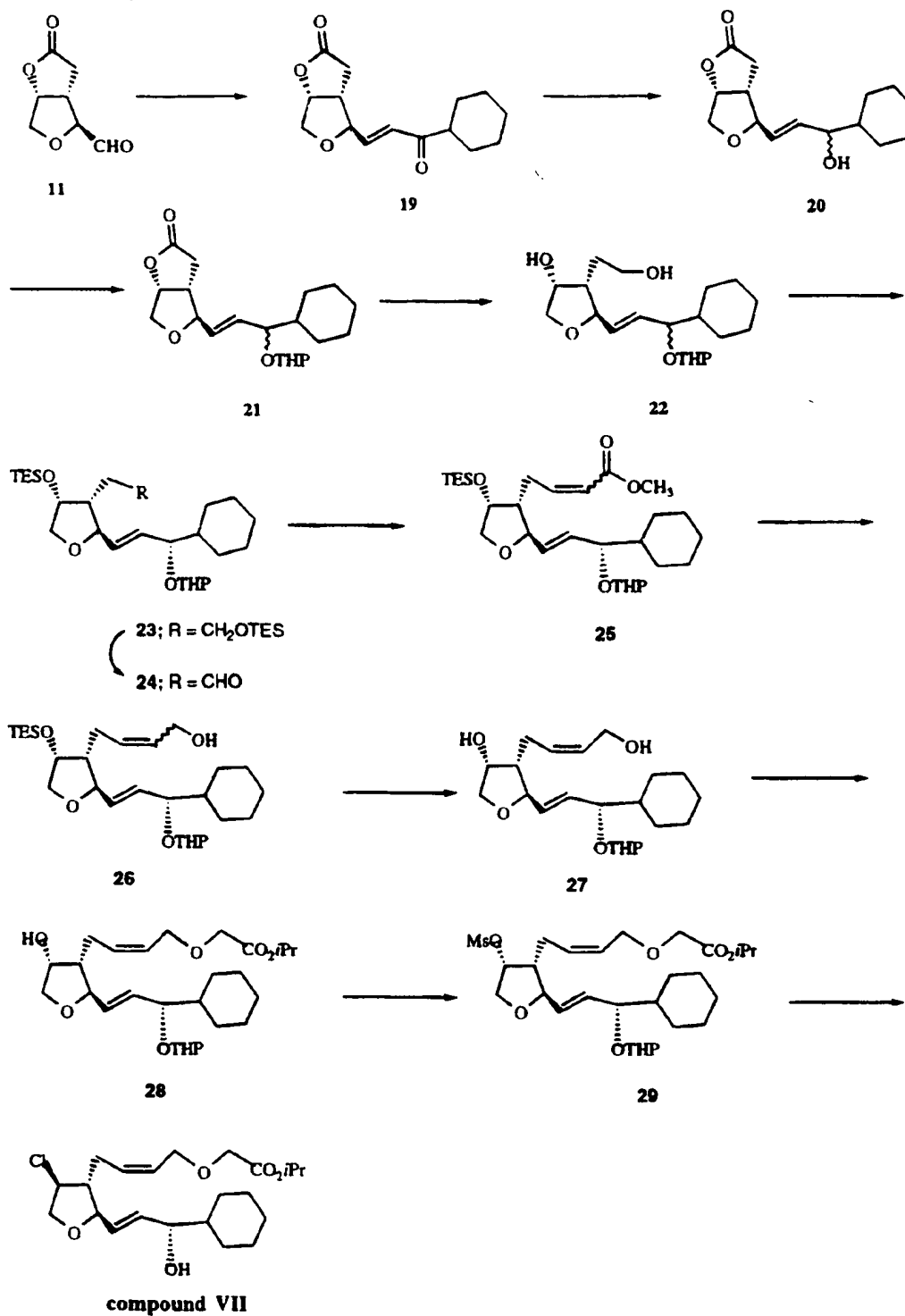
A solution of the acid **18** (0.25 g, 0.61 mmol) in 15 mL of acetone was treated with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU; 0.66 mL, 4.4 mmol) for 30 min at room temperature. Isopropyl iodide (0.36 mL, 3.7 mmol) was then added to the reaction mixture, and the resulting solution was stirred at room temperature for 18 h. The solvent was then evaporated and the residue was partitioned between 50 mL of Et₂O and 10 mL of water. The layers were separated and the organic layer was washed with 3 X 10 mL of a 10 % aqueous CuSO₄ solution and 1X10 mL of brine. The organic phase was dried (Na₂SO₄), filtered and concentrated. The crude was applied to a column of silica gel and

the two diastereomeric esters were isolated separately, yielding compound VI (81 mg, 32% yield) as a colorless oil: R_f 0.54 (EtOAc); $^1\text{H-NMR}$ (CDCl_3) δ 7.19 (m, 1H), 6.92 (m, 2H), 6.80 (m, 1H), 5.86 (m, 2H), 5.42 (m, 2H), 5.05 (septet, $J = 6.2$ Hz, 1H), 4.58 (m, 1H), 4.35 (m, 1H), 4.20 - 3.82 (broad m, 5H), 2.68 (d, $J = 4.5$ Hz, 1H), 2.45 - 2.00 (m, 7H), 1.89 - 1.60 (m, 4H), 1.24 (d, $J = 6.5$ Hz, 6H); $^{13}\text{C-NMR}$ (CDCl_3) δ 173.42, 159.20, 134.89, 132.48, 130.57, 130.35, 130.25, 128.06, 121.35, 115.11, 113.05, 82.02, 75.43, 72.70, 71.87, 70.14, 67.71, 51.09, 33.99, 26.63, 24.77, 22.57, 21.81; MS m/z at 475 for (M+Na).

10 **EXAMPLE 3: SYNTHESIS OF Isopropyl [2*R*(1*E*,3*S*),3*R*(5*Z*),4*S*]-7-[Tetrahydro-4-chloro-2-(3-cyclohexyl-3-hydroxy-1-propenyl)-3-furanyl]-3-oxa-5-heptenoate (VII)**

Compound VII may be prepared as described by the following Scheme 3.

Scheme 3: Synthesis of compound VII:



A:[3aR, 4R(1E), 6aR]-4-(3-Cyclohexyl-3-oxopropenyl)hexahydrofuro[3,4-b]furan-2-one (19):

A 500 mL 1-neck flask was charged with dimethyl-(2-cyclohexyl-2-oxo)ethylphosphonate
5 (6.9 g, 29.6 mmol), LiCl (1.07 g, 25.4 mmol) and 40 mL of anhydrous THF. The mixture
was cooled to 0°C and triethylamine (3.6 mL, 25.4 mmol) was added to it in a dropwise
manner. The white slurry formed was stirred for 10 min and then a solution of (3aR,4S,6aR)-
hexahydro-2-oxofuro[3,4-b]furan-4-carboxaldehyde (**11**: 3.31 g, 21.2 mmol) in a mixture of
60 mL of anhydrous THF and 10 mL of anhydrous CH₂Cl₂ was added to it dropwise. The
10 resulting mixture was allowed to warm to room temperature and was stirred at that
temperature for 18 h. The reaction mixture was worked up (250 mL of EtOAc and 50 mL of
water) and purified by silica gel chromatography. The white solid obtained was recrystallized
from hexane using a minimum amount of EtOAc to effect solubilization. The enone **19** (2.2
g, 43% yield) was isolated as white needles: mp. 80.0-82.5°C; R_f 0.37 (60% EtOAc/hexane);
15 [α]_D²² +47.9° (c = 0.6, CH₃OH); ¹H-NMR (CDCl₃) δ 6.72 (dd, J = 16.6, 4.5 Hz, 1H), 6.45
(dd, J = 16.6, 1.5 Hz, 1H), 5.12 (m, 1H), 4.38 (m, 1H), 4.20 - 4.05 (m, 2H), 2.85 (m, 2H),
2.52 (m, 2H), 1.95 - 1.58 (m, 5H), 1.50 - 1.10 (m, 5H); ¹³C-NMR (CDCl₃) δ 202.32, 175.18,
141.00, 127.81, 83.86, 83.80, 72.74, 49.64, 44.65, 32.86, 28.31, 25.76, 25.57; MS m/z at
265 for (M+H)⁺.

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B:[3aR, 4R(1E,3RS), 6aR]-4-(3-Cyclohexyl-3-hydroxypropenyl)hexahydrofuro[3,4-b]furan-2-one (20):

To a solution of CeCl₃·7H₂O (2.23 g, 6.0 mmol) in 50 mL of methanol, the enone **19** (0.8
25 g, 3.0 mmol) was added and the resulting solution was cooled to 0°C. The cold solution was
treated with solid NaBH₄ in small portions (0.23 g, 6.0 mmol) over a period of 5 min.
(CAUTION: vigorous H₂ gas evolution occurs). After an additional 3 min at 0°C, the
reaction was quenched by pouring it into 50 mL of a 0.5 N aqueous HCl solution. The
aqueous layer was extracted with 4 X 75 mL of CHCl₃ and the organic extracts were washed
30 with water and brine and dried (MgSO₄). Filtration and solvent removal afforded the crude,
which was purified by silica column chromatography to afford **20** (0.69 g, 85% yield) as an

equimolar mixture of two diastereomers: R_f 0.2 (60% EtOAc/hexane); $^1\text{H-NMR}$ (CDCl_3) δ 5.77 (m, 2H), 5.12 (m, 1H), 4.25 - 3.82 (m, 4H), 2.78 (m, 2H), 2.45 (m, 1H), 1.90 - 0.85 (broad m, 12H).

5 **C:[3aR, 4R(1E,3RS), 6aR]-4-[3-Cyclohexyl-3-(tetrahydropyran-2-yl)oxypropenyl]-hexahydrofuro[3,4-b]furan-2-one (21):**

A solution of the alcohol **20** (0.69 g, 2.6 mmol) and 3,4-dihydro-2H-pyran (0.6 mL, 5.2 mmol) in 25 mL of CH_2Cl_2 was cooled to 0°C . After 3 min, a catalytic amount of
10 *p*-toluenesulfonic acid (20 mg) was added. The reaction mixture was stirred at 0°C for 20 min and then quenched by the addition of 10 mL of a saturated aqueous solution of NaHCO_3 . The layers were separated and the organic phase was washed with brine and dried (K_2CO_3). The compound **21** (0.8 g, 88% yield) was isolated as a colorless liquid after chromatography of the crude on silica: R_f 0.5 (60% EtOAc/hexane).

15

D:[2R(1E,3S),3R, 4R]-2-[3-Cyclohexyl-3-(tetrahydropyran-2-yl)oxy-1-propenyl]-3-(2-triethylsilyloxyethyl)-4-triethylsilyloxytetrahydrofuran (23):

A suspension of lithium aluminum hydride (2.0 g, 54 mmol) in dry THF (100 mL) was
20 cooled to 0°C , and to it a solution of the lactone **21** (9.42 g, 27 mmol) in THF (100 mL) was added dropwise. The mixture was gradually allowed to warm to room temperature, and was stirred at that temperature for 14 h. The reaction was then cooled to 0°C in an ice bath, and quenched by adding 10 mL of methanol dropwise. The ice bath was removed and the suspension was sequentially treated with 2 mL of water, 2 mL of a 15% aqueous NaOH
25 solution and 6 mL of water. The resulting suspension was filtered through a pad of MgSO_4 , and the filter cake was washed with 100 mL of EtOAc. The filtrate was concentrated and the residue was subjected to silica gel chromatography to afford 7.14 g (75% yield) of the diol **22** (mixture of diastereomers) as a colorless liquid: R_f 0.25 (EtOAc); $^1\text{H-NMR}$ (d_6 -DMSO) δ (partial spectrum) 5.65-5.30 (m, broad, 2H, olefinic), 4.75 (m, 1H, OH), 4.45 (m, 1H, OH).

30

A solution of the diol **22** (1.84 g, 5.2 mmol) in CH₂Cl₂ (60 mL) was cooled to 0 °C, and to it was added triethylamine (4.4 mL, 31.2 mmol) and a catalytic amount of *N,N*-dimethylamino pyridine (DMAP, 50 mg). The resulting mixture was stirred for 3 min, and then triethylsilyl chloride (2.6 mL, 15.6 mmol) was added to it. The reaction mixture was stirred for 1 h at 0 °C, and then at room temperature for an additional hour. The reaction was then poured into 100 mL of water, and the biphasic mixture was extracted with ether (5 X 50 mL). The organic extracts were combined and washed with brine and dried over anhydrous K₂CO₃. Filtration and solvent removal gave an oil, which was subjected to column chromatography on silica gel; the two C15 diastereomers were separated and the desired isomer **23** (1.63 g, 54%) was obtained as a colorless oil: R_f 0.21 (20% Et₂O/hexane); ¹H-NMR (CDCl₃) δ 5.50 (m, 2H), 4.70 (broad m, 1H), 4.32 (broad m, 1H), 4.15-3.40 (broad, 8H), 2.15-1.45 (broad, 15H), 1.35-0.80 (m, 20H), 0.60 (m, 12H).

E:[2R(1E,3S),3R,4R]-2-[Tetrahydro-2-[3-cyclohexyl-3-(tetrahydropyran-2-yl)oxy-1-propenyl]-4-triethylsilyloxy-3-furanyl]acetaldehyde (24):

A solution of oxalyl chloride (2.8 mL, 2.0 M/CH₂Cl₂, 5.60 mmol) in 15 mL of CH₂Cl₂ was cooled to -78 °C, and to it a solution of DMSO (0.80 mL, 11.20 mmol) in 1.0 mL of CH₂Cl₂ was added dropwise. The mixture was stirred for 3 min, at which time a solution of the substrate **23** (1.63 g, 2.80 mmol) in 15 mL of CH₂Cl₂ was added to it. The resulting mixture was stirred at -78 °C for 3 h, and then treated with triethylamine (2.0 mL, 14.0 mmol). The cold temperature bath was removed and the reaction was allowed to warm to room temperature and then worked up by partitioning between water and CH₂Cl₂. The crude was subjected to silica gel chromatography to afford **24** (1.02 g, 78% yield) as a colorless liquid: R_f 0.15 (10% EtOAc/hexane); ¹H-NMR (CDCl₃) δ (partial spectrum) 9.84 (s, 1H, aldehyde), 5.53 (m, 2H, olefinic), 4.69 (m, 1H), 4.50 (m, 1H), 4.15 (m, 2H), 2.80 (m, 1H).

F: Methyl [2R(1E,3S),3R(2EZ),4R]-4-[Tetrahydro-2-[3-cyclohexyl-3-(tetrahydropyran-2-yl)oxy-1-propenyl]-4-triethylsilyloxy-3-furanyl]-2-butenolate (25):

A solution containing bis(2,2,2-trifluoroethyl)(methoxycarbonylmethyl)phosphonate (0.86 g, 2.6 mmol) and 18-crown-6 (1.74 g, 6.6 mmol) in THF (30 mL) was cooled to -78 °C, and to it a solution of potassium bis(trimethylsilyl)amide (KHMDs, 5.2 mL, 0.5 M in toluene, 2.6 mmol) was added dropwise. The resulting solution was stirred at -78 °C for 20 min, at which time a solution of the aldehyde **24** (1.02 g, 2.2 mmol) in 10 mL of THF was introduced via cannula. The reaction was stirred at the same temperature for 2 h, after which it was rapidly warmed to 0 °C (ice bath) and quenched at that temperature by adding 50 mL of a saturated aqueous solution of NH₄Cl. The resulting mixture was allowed to warm to room temperature and was partitioned between water and EtOAc. The organic layers were combined, washed with water, brine and dried (MgSO₄). The product **25** (0.94 g, 81% yield), as a mixture of diastereomers, was isolated as a colorless liquid after chromatography on silica: R_f 0.50 (30% EtOAc/hexane); ¹H-NMR (CDCl₃) δ (major isomer only) 6.28 (m, 1H), 5.80 (m, 1H), 5.55 (m, 2H), 4.68 (m, 1H), 4.38 (m, 1H), 4.18 (m, 1H), 4.02 (m, 1H), 3.70 (s, 3H), 2.80 (m, 2H), 0.95 (m, 9H), 0.61 (m, 6H).

G: [2R(1E,3S),3S(2Z),4R]-4-[Tetrahydro-2-[3-cyclohexyl-3-(tetrahydropyran-2-yl)oxy-1-propenyl]-4-hydroxy-3-furanyl]-2-butenol (27):

A solution of the enoate **25** (0.94 g, 1.8 mmol) in 20 mL of THF was cooled to 0 °C, and DIBAL-H (3.6 mL, 1.5 M in toluene, 5.4 mmol) was added to it dropwise over 5 min. The reaction mixture was stirred at 0 °C for 2 h, and then quenched at the same temperature by carefully adding 5 mL of methanol. The reaction was worked up by stirring it with a saturated aqueous solution of potassium sodium tartrate for 1 h at room temperature. The layers were separated and the aqueous layer was extracted with 3 X 25 mL of ether. The organic extracts were combined and dried, filtered and evaporated to afford an oil which was purified by passage through a short plug of silica. The mixture of allylic alcohol isomers **26** (0.77 g, 82% yield) was obtained as a colorless liquid: R_f 0.23 (30% EtOAc/hexane).

A solution of the allylic alcohol mixture obtained above (0.77 g, 1.56 mmol) in 50 mL of THF was treated with tetra-n-butylammonium fluoride (8.0 mL, 1.0 M in THF, 8.0 mmol) at room temperature for 10 min. The mixture was then poured into water and extracted with ether (3 X 25 mL). The combined ether layers were washed with water and brine and dried
 5 (MgSO₄); the crude oil was subjected to chromatography to afford the desired major isomer 27 (0.54 g, 91% yield) as a white semi-solid: *R*_f 0.31 (EtOAc); ¹H-NMR (CDCl₃) δ (partial spectrum) 5.90-5.45 (broad m, 4H), 4.68 (m, 1H), 4.35 (m, 2H), 4.20-3.65 (broad m, 6H), 3.45 (m, 1H), 2.60 (m, 2H); MS *m/z* at 403 for (M+Na)⁺.

10 **H: Isopropyl [2*R*(1*E*,3*S*),3*S*(5*Z*),4*R*]-7-[Tetrahydro-2-[3-cyclohexyl-3-(tetrahydropyran-2-yl)oxy-1-propenyl]-4-hydroxy-3-furanyl]-3-oxa-5-heptenoate (28):**

A solution of the diol 27 (0.54 g, 1.42 mmol) in 15 mL of toluene was cooled to 0 °C, and to it were added nBu₄NHSO₄ (0.1 g) and aqueous NaOH (15 mL, 25% w/v). The resulting
 15 mixture was stirred vigorously for 5 min, at which time isopropyl bromoacetate (0.77 g, 4.26 mmol) was added to it dropwise. After stirring at 0 °C for an additional 30 min, the reaction mixture was poured into ether/water mixture (50 mL each). The layers were separated and the aqueous layer was extracted with ether (3 X 25 mL). The organic extracts were combined and washed with a saturated aqueous solution of KH₂PO₄ (10 mL), water (10 mL) and brine
 20 (10 mL) and dried (MgSO₄). The crude oil was subjected to silica column chromatography to afford 28 (0.45 g, 66% yield) as a colorless liquid: *R*_f 0.28 (60% EtOAc/hexane); ¹H-NMR (CDCl₃) δ 5.72 (m, 2H), 5.52 (m, 2H), 5.13 (septet, *J* = 6.7 Hz, 1H), 4.70 (m, 1H), 4.45-4.25 (m, 2H), 4.20-3.68 (broad m, 8H), 3.45 (m, 1H), 3.28 (m, 1H), 2.60 (m, 1H), 2.08-1.35 (broad m, 15H), 1.28 (d, *J* = 7.2 Hz, 6H), 1.25-0.90 (broad m, 3H).

25

I: Isopropyl [2*R*(1*E*,3*S*),3*R*(5*Z*),4*S*]-7-[Tetrahydro-4-chloro-2-[3-cyclohexyl-3-hydroxy-1-propenyl]-3-furanyl]-3-oxa-5-heptenoate (compound VII):

A solution of the ester 28 (0.2 g, 0.4 mmol) in 5.0 mL of anhydrous pyridine was cooled
 30 to 0 °C, and to it methanesulfonyl chloride (80 mL, 1.04 mmol) was added. The resulting solution was stirred at 0 °C for 5 min and then at room temperature for 24 h. The reaction

mixture was poured into 50 mL of ether and washed with 4 X 25 mL of a saturated aqueous CuSO₄ solution and dried (MgSO₄). The crude was purified by passage through a column of silica to afford 0.21 g (97% yield) of the mesylate **29** as a pale yellow liquid: R_f 0.30 (60% EtOAc/hexane).

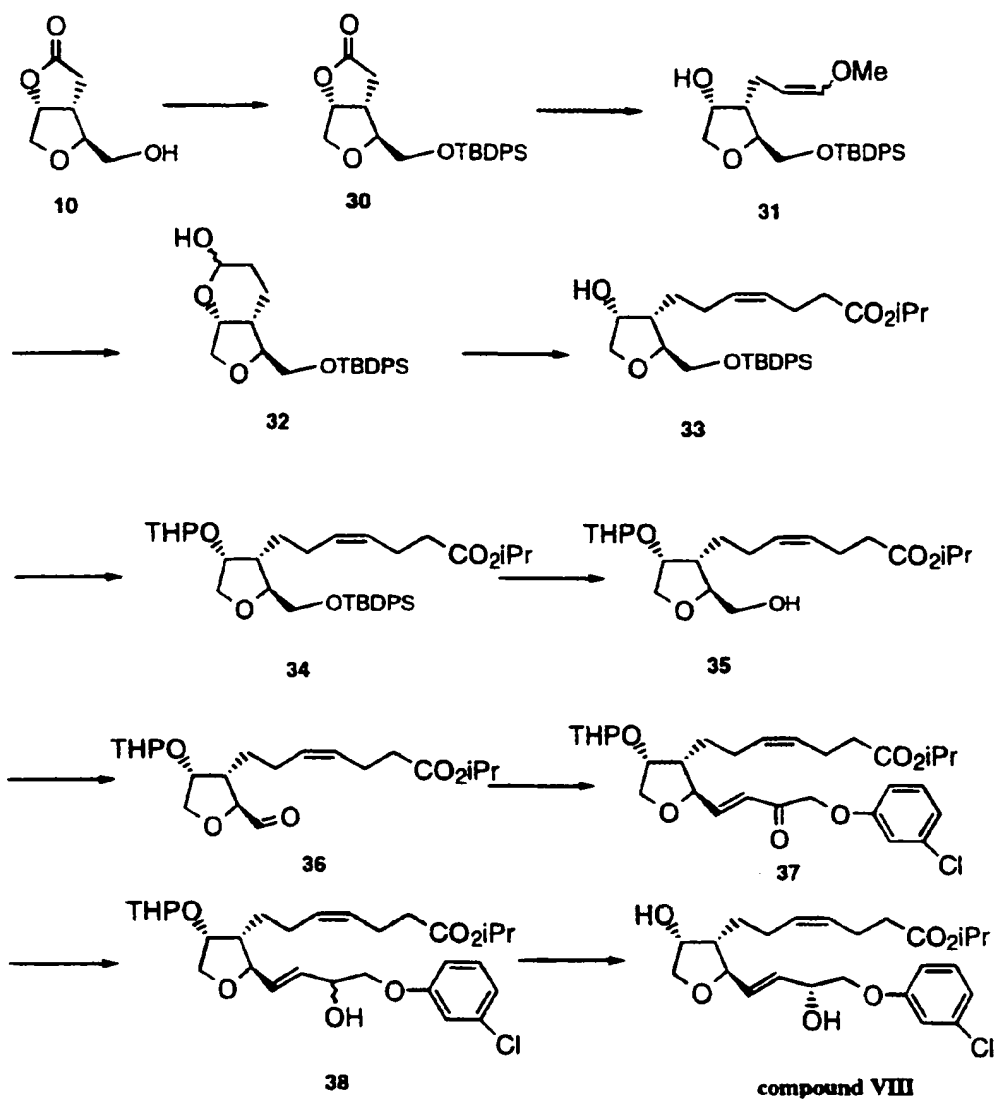
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The mesylate **29** obtained above (0.21 g, 0.39 mmol), and LiCl (0.17 g, 4.0 mmol) were dissolved in 10 mL of anhydrous DMF and the resulting solution was heated at 65-75 °C for 24 h. The reaction was cooled to room temperature, and poured into ether/water. The layers were separated, the aqueous layer was extracted with 3X25 mL of ether; the organic layers
10 were combined and washed with 2X10 mL water and brine and dried (Na₂SO₄). Filtration and solvent removal followed by chromatography of the crude on silica afforded compound **VII** (51 mg, 32% yield) as a colorless oil: R_f 0.50 (60% EtOAc/hexane); ¹H-NMR (CDCl₃) δ 5.82-5.60 (broad m, 4H), 5.08 (septet, *J* = 6.7 Hz, 1H), 4.20-3.82 (broad m, 10H), 2.32 (m, 2H), 2.15 (m, 1H), 1.90-1.55 (broad m, 8H), 1.50-0.90 (broad m, 8H), 1.28 (d, *J* = 7.3 Hz,
15 6H); ¹³C-NMR (CDCl₃) δ 169.92, 135.26, 130.32, 130.19, 127.86, 83.97, 76.57, 74.22, 68.63, 67.69, 66.60, 59.96, 54.73, 43.61, 28.90, 28.48, 27.87, 26.54, 26.16, 26.09, 21.89; MS *m/z* at 437 for (M+Na)⁺.

20 **EXAMPLE 4: SYNTHESIS OF Isopropyl [2*R*(1*E*,3*R*),3*S*(4*Z*),4*R*]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-hydroxy-3-furanyl]-4-heptenoate (VIII)**

Compound **VIII** may be prepared as described in the following Scheme 4.

Scheme 4: Synthesis of compound VIII



A: (3aR,4S,6aR)-4-(tert-Butyldiphenylsilyloxy)methylhexahydrofuro[3,4-b]furan-2-one (30):

A mixture of alcohol **10** (5.0 g, 31.6 mmol) and imidazole (4.3 g, 63.2 mmol) was dissolved in 100 mL of anhydrous DMF. To this solution *tert*-butyldiphenylsilyl chloride (10.4 g, 38.0 mmol) was added and the resulting mixture was stirred at room temperature for 14 h. The solvent was evaporated and the residue was taken up in 100 mL of EtOAc, washed with water (2X50 mL), dilute aqueous solution of HCl (2X50 mL) and brine and dried (MgSO₄). The solvent was evaporated and the crude was purified by chromatography on silica gel to afford **30** (12.4 g, quantitative yield) as a white solid: *R*_f 0.6 (60% EtOAc/hexanes); ¹H-NMR (CDCl₃) δ 7.65 (m, 4H), 7.42 (m, 6H), 5.10 (m, 1H), 4.25 (dd, *J* = 12, 4 Hz, 1H), 4.05 (dd, *J* = 12, 2 Hz, 1H), 3.85 (m, 1H), 3.75 (m, 2H), 3.00 (m, 1H), 2.82 (dd, *J* = 16, 7 Hz, 1H), 2.45 (dd, *J* = 16, 2 Hz, 1H), 1.05 (s, 9H).

B: Isopropyl [2S,3S(4Z),4R]-7-[Tetrahydro-2-(tert-butyldiphenylsilyloxy)methyl-4-hydroxy-3-furanyl]-4-heptenoate (33):

A solution of the lactone **30** (5.7 g, 14.5 mmol) in 150 mL of anhydrous THF was cooled to -78 °C under an inert atmosphere, and to it DIBAL-H (14.5 mL, 1.5 M in toluene, 21.7 mmol) was added dropwise. The resulting mixture was stirred at -78 °C for 1.5 h and was then quenched at the same temperature by the addition of 5 mL of methanol. The reaction was warmed to room temperature, an equal volume of a saturated aqueous solution of potassium sodium tartrate was added to it and the resulting slurry was stirred at room temperature for 1 h. The layers were separated, and the aqueous layer was extracted with 3X25 mL of EtOAc. The organic layers were combined and washed with brine and dried (MgSO₄). The solution was filtered and concentrated and the crude was purified by passage through a short column of silica gel to afford the intermediate lactol (5.6 g, quantitative yield) as a colorless oil: *R*_f 0.5 (60% EtOAc/hexanes).

A suspension of (methoxymethyl)triphenylphosphonium chloride (2.5 g, 7.5 mmol) in 70 mL of dry THF was cooled to 0 °C under a N₂ atmosphere. To this solution

potassium *tert*-butoxide (*t*-BuOK, 9.0 mL, 1.0 M in THF, 9.0 mmol) was added dropwise and stirring was continued at 0 °C for an additional 20 min. At this time a solution of the lactol obtained above (1.0 g, 2.5 mmol) in 30 mL of dry THF was added to it, and the resulting mixture was stirred at 0 °C for 1.5 h. The reaction was then worked up by
5 pouring it into 50 mL of a saturated aqueous solution of KH_2PO_4 , the layers were separated and aqueous layer was extracted with 3X25 mL of EtOAc. The combined organic layers were washed with water and brine and dried (MgSO_4); solvent removal and chromatography of the crude on silica afforded the enolether **31** (0.89 g, 83% yield) as a colorless liquid: R_f 0.6 (60% EtOAc/hexanes).

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A solution containing enolether **31** (2.45 g, 5.7 mmol), *p*-toluenesulfonic acid (0.1 g) and water (10 mL) in 150 mL of THF was heated at reflux for 3 h. The mixture was then cooled to room temperature and poured into 50 mL of a saturated aqueous solution of NaHCO_3 . The layers were separated and aqueous layer was extracted with EtOAc. The
15 organic extracts were combined and dried (MgSO_4) and the crude product was subjected to chromatography on silica to afford **32** (1.44 g, 60% yield) as a colorless liquid. This material was used in the next reaction: R_f 0.28 (50% EtOAc/hexanes).

A suspension of (3-carboxypropyl)triphenylphosphonium bromide (4.5 g, 10.5
20 mmol) in 70 mL of dry THF was cooled to 0 °C and to it *t*-BuOK (21.0 mL, 1.0 M in THF, 21.0 mmol) was added dropwise. The resulting solution of the ylid was stirred for 30 min at 0 °C and to it a solution of the lactol **32** (1.44 g, 3.5 mmol) in 30 mL of dry THF was added dropwise over a period of 10 min. The reaction was allowed to warm to room temperature gradually, and was stirred at that temperature for 14 h. The mixture was then
25 poured into 50 mL of a saturated aqueous solution of KH_2PO_4 , and extracted with 3X25 mL of EtOAc. The organic extracts were combined and washed with brine and dried (MgSO_4). Filtration and solvent removal afforded an oily residue which was used immediately in the subsequent step.

30 The crude product from above was dissolved in 40 mL of acetone and the solution was treated with DBU (12.0 mL, 84 mmol) at room temperature for 10 min. Isopropyl

iodide (7.0 mL, 70 mmol) was then introduced and the resulting mixture was stirred at room temperature for 18 h. Solvent was then evaporated and the residue was dissolved in 50 mL of EtOAc. This solution was washed sequentially with 3X25 mL of a saturated aqueous solution of KH_2PO_4 , 1X10 mL of water and brine and dried over anhydrous MgSO_4 . Filtration, solvent removal and chromatography of the crude on silica gel afforded the desired isopropyl ester **33** (1.18 g, 65% yield from **32**) as a slightly yellow liquid: R_f 0.2 (30% EtOAc/hexanes); $^1\text{H-NMR}$ (CDCl_3) δ 7.71 (m, 4H), 7.40 (m, 6H), 5.38 (m, 2H), 5.00 (septet, $J = 6.4$ Hz, 1H), 4.38 (m, 1H), 3.65-4.00 (broad m, 5H), 1.90-2.50 (broad m, 7H), 1.55 (m, 2H), 1.23 (d, $J = 7.2$ Hz, 6H), 1.05 (s, 9H); MS m/z at 547 for (M+Na) $^+$.

C: Isopropyl [2S,3R(4Z),4R]-7-[Tetrahydro-2-hydroxymethyl-4-(tetrahydropyran-2-yl)oxy-3-furanyl]-4-heptenoate (35):

A solution of the alcohol **33** (1.18 g, 2.3 mmol) and 3,4-dihydro-2H-pyran (0.3 mL, 3.4 mmol) in 50 mL of CH_2Cl_2 was cooled to 0 °C and to it a catalytic amount of *p*-toluenesulfonic acid (10 mg) was added. The resulting mixture was stirred at 0 °C for 25 min and was then quenched by the addition of 25 mL of a saturated aqueous solution of NaHCO_3 . The mixture was warmed to room temperature, the layers were separated and the aqueous layer was extracted with 3X25 mL of CH_2Cl_2 . The organic layers were combined and washed with brine and dried (K_2CO_3). The crude obtained after filtration and solvent removal was purified by passage through a short plug of silica to afford the intermediate tetrahydropyranyl ether **34** as colorless liquid: R_f 0.4 (30% EtOAc/hexanes).

The silyl ether **34** thus obtained was dissolved in 20 mL of THF and the solution was treated with tetra-*n*-butylammonium fluoride (7.0 mL, 1.0 M in THF, 7.0 mmol) at room temperature for 2 h. The reaction mixture was then poured into water and was extracted with EtOAc (3X25 mL). The organic extracts were combined and dried (MgSO_4), filtered and concentrated. The crude was subjected to chromatography on silica to afford the alcohol **35** (0.72 g, 85% yield from **33**) as a colorless liquid: R_f 0.16 (50%

EtOAc/hexanes): $^1\text{H-NMR}$ (d_6 -DMSO) δ (partial spectrum) 5.36 (m, 2H), 4.87 (septet, $J = 6.5$ Hz, 1H), 4.60 (m, 2H), 1.18 (d, $J = 7.2$ Hz, 6H).

5 **D: Isopropyl [2S,3R(4Z),4R]-7-[Tetrahydro-2-formyl-4-(tetrahydropyran-2-yl)oxy-3-furanyl]-4-heptenoate (36):**

A solution of oxalyl chloride (2.0 mL, 2.0 M in CH_2Cl_2 , 4.0 mmol) in 10 mL of dry CH_2Cl_2 was cooled to -78°C , and to it a solution of DMSO (0.56 mL, 8.0 mmol) in 5 mL of CH_2Cl_2 was introduced dropwise. After the mixture was stirred for 3 min at -78°C , a
10 solution of the substrate 35 (0.72 g, 2.0 mmol) in 25 mL of CH_2Cl_2 was added to it dropwise. The mixture was stirred for 15 min, at which time triethylamine (1.7 mL, 12.0 mmol) was introduced, and stirring was continued for an additional 15 min. The reaction was gradually warmed to room temperature and then poured into 50 mL of water. The layers were separated and the water layer was extracted with 3X25 mL of CH_2Cl_2 . The
15 combined organic extracts were washed with water and brine and dried (MgSO_4). Filtration and solvent removal, followed by chromatography of the crude on silica afforded the aldehyde 36 (0.69 g, 94% yield) as a pale yellow liquid: R_f 0.3 (50% EtOAc/hexanes); $^1\text{H-NMR}$ (CDCl_3) δ (partial spectrum) 9.66 (d, $J = 3$ Hz, 1H), 5.37 (m, 2H), 5.0 (septet, $J = 6.5$ Hz, 1H), 1.24 (d, $J = 7.2$ Hz, 6H).

20

E: Isopropyl [2R(1E),3R(4Z),4R]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-oxo-1-butenyl]-4-(tetrahydropyran-2-yl)oxy-3-furanyl]-4-heptenoate (37):

A mixture of the aldehyde 36 (0.32 g, 0.87 mmol), dimethyl-3-(3-chlorophenoxy)-
25 2-oxopropylphosphonate (1.0 g, 3.5 mmol) and LiCl (0.15 g, 3.5 mmol) was taken up in 40 mL of dry THF, and the solution was cooled to 0°C under a N_2 atmosphere. To this solution, triethylamine (0.5 mL, 3.5 mmol) was added dropwise, and the resulting slurry was stirred at 0°C for 1 h. The reaction was then quenched by pouring it into 50 mL of a saturated aqueous solution of KH_2PO_4 . The organic layer was separated and the aqueous
30 layer was extracted with 3X25 mL of EtOAc. The organic extracts were combined and washed with water and brine and dried (MgSO_4). The crude product mixture was

subjected to chromatography on silica to afford the enone **37** (0.34 g, 73% yield) as a pale yellow liquid: R_f 0.6 (60% EtOAc/hexanes); $^1\text{H-NMR}$ (CDCl_3) δ (partial spectrum) 6.70-7.20 (broad m, 5H), 6.12 (d, $J = 16.7$ Hz, 1H), 5.36 (m, 2H), 5.0 (septet, $J = 6.5$ Hz, 1H), 4.73 (s, 2H), 1.23 (d, $J = 7.5$ Hz, 6H).

5

F: Isopropyl [2*R*(1*E*,3*RS*),3*R*(4*Z*),4*R*]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-(tetrahydropyran-2-yl)oxy-3-furanyl]-4-heptenoate (38**):**

A mixture of the enone **37** (0.34 g, 0.64 mmol) and $\text{CeCl}_3 \cdot 7\text{H}_2\text{O}$ (0.47 g, 1.27 mmol) was dissolved in 30 mL of methanol and the solution was cooled to -5°C . NaBH_4 (47 mg, 1.27 mmol) was added to the solution in small portions over a period of 3 min. The mixture was stirred for an additional 3 min and the reaction was quenched at -5°C by the addition of 10 mL of a saturated aqueous solution of NH_4Cl . The resulting slurry was warmed to room temperature and partitioned between CHCl_3 and water. The aqueous layer was extracted with 3X25 mL of CHCl_3 and the combined organic extracts were washed with 2X10 mL of water and brine. The organic layer was dried, filtered and concentrated and the crude was purified by chromatography on silica to afford the reduction product **38** (0.30 g, 87% yield) as a colorless liquid: R_f 0.24 (50% EtOAc/hexanes).

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G: Isopropyl [2*R*(1*E*,3*R*),3*S*(4*Z*),4*R*]-7-[Tetrahydro-2-[4-(3-chlorophenoxy)-3-hydroxy-1-butenyl]-4-hydroxy-3-furanyl]-4-heptenoate (compound VIII):

The allyl alcohol **38** (0.30 g, 0.55 mmol) was dissolved in a mixture of 10 mL of methanol and 1.0 mL of water, and the solution was cooled to 0°C . Approximately 10 drops of 12 N HCl was added to it dropwise and the mixture was stirred at 0°C for 15 min and then at room temperature for 1 h. The reaction was then quenched by the addition of solid NaHCO_3 , and the suspension was partitioned between CHCl_3 /water. The layers were separated and the aqueous layer was extracted with 3X25 mL of CHCl_3 . The organic extracts were combined and washed with water (2X10 mL) and brine and dried (Na_2SO_4). Filtration and solvent removal gave an oil which was subjected to silica gel

30

chromatography. The two diastereomers were isolated separately, and the desired compound **VIII** (61 mg, 25% yield) was obtained as colorless liquid: R_f 0.15 (60% EtOAc/hexanes); $^1\text{H-NMR}$ (CDCl_3) δ 7.17 (m, 1H), 6.90 (m, 2H), 6.78 (m, 1H), 5.84 (m, 2H), 5.35 (m, 2H), 5.00 (septet, $J = 6.4$ Hz, 1H), 4.55 (m, 1H), 4.40 (m, 1H), 3.80-4.15 (broad m, 5H), 1.90-2.65 (broad m, 8H), 1.75 (m, 2H), 1.45 (m, 2H), 1.21 (d, $J = 7.4$ Hz, 6H); $^{13}\text{C-NMR}$ (CDCl_3) δ 173.08, 159.19, 134.90, 132.69, 130.68, 130.57, 130.26, 128.07, 121.35, 115.09, 113.04, 82.21, 75.45, 72.62, 71.83, 70.12, 67.94, 50.84, 34.36, 25.78, 24.55, 22.70, 21.89, 21.80; HRMS m/z calculated for $\text{C}_{24}\text{H}_{33}\text{O}_6\text{ClNa}$ ($\text{M}+\text{Na}^+$) 475.185884, found 475.18588.

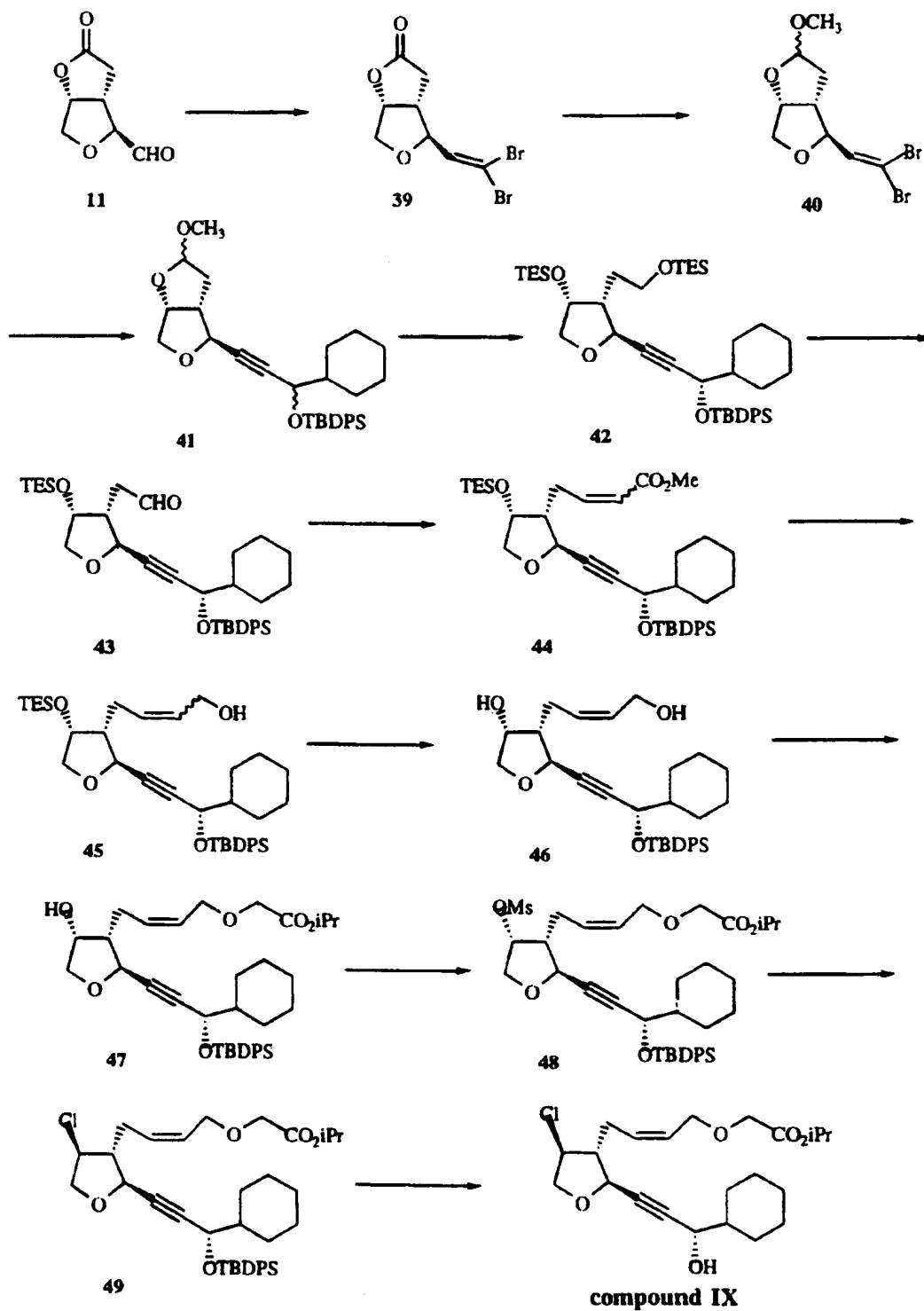
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EXAMPLE 5: Synthesis of Isopropyl [2*S*(3*S*),3*R*(5*Z*),4*S*]-7-[Tetrahydro-4-chloro-2-(3-cyclohexyl-3-hydroxy-1-propynyl)-3-furanyl]-3-oxa-5-heptenoate (IX)

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Compound **IX** may be prepared as described in the following Scheme 5.

Scheme 5: Synthesis of Compound IX:



Isopropyl [2S(3S),3R(5Z),4S]-7-[Tetrahydro-4-chloro-2-(3-cyclohexyl-3-hydroxy-1-propynyl)-3-furanyl]-3-oxa-5-heptenoate (IX)

The aldehyde 11 is treated with CBr₄ and triphenylphosphine to form the dibromoolefin 39. Lactone 39 is reduced to the lactol with diisobutylaluminum hydride (DIBAL-H) and this intermediate is reacted with trimethyl orthoformate in the presence of a catalytic amount of *p*-toluenesulfonic acid to afford the methyl glycoside 40. Treatment of compound 40 with *n*-BuLi followed by cyclohexanecarboxaldehyde yields the propargyl alcohol intermediate, which is reacted with *tert*-butyldiphenylsilyl chloride in the presence of base to afford the silyl ether 41. The methylglycoside moiety is removed by treatment of 41 with *p*-toluenesulfonic acid in refluxing THF/water, and the intermediate lactol is further reduced with DIBAL-H to the diol; treatment of the intermediate diol with chlorotriethylsilane (3 equivalents) under standard conditions, followed by separation of the diastereomers by column chromatography on silica affords the fully protected compound 42. Swern oxidation of 42 affords the aldehyde 43, which is homologated with bis(2,2,2-trifluoroethyl)(methoxycarbonylmethyl)phosphonate in the presence of KHMDS to give the diastereomeric mixture of crotonates 44. The ester 44 is reduced with DIBAL-H to the diastereomeric mixture of allylic alcohols 45 which is selectively deprotected (AcOH, H₂O, THF, room temperature), and the intermediate diol diastereomers are separated by column chromatography to afford the allylic alcohol 46. The diol 46 is alkylated with isopropyl bromoacetate under phase-transfer conditions (toluene, H₂O, NaOH, (*n*-Bu)₄NHSO₄, 0 °C) to give the ester 47, which is reacted with methanesulfonyl chloride in the presence of pyridine to afford the mesylate 48. Treatment of the mesylate 48 with LiCl in DMF at 80 °C gives the chlorinated compound 49 which when reacted with tetra-*n*-butylammonium fluoride affords compound IX.

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The substituted tetrahydrofurans of the present invention may be formulated in various pharmaceutical compositions for administering to humans and other mammals as a treatment of glaucoma or ocular hypertension. As used herein, the term "pharmaceutically effective amount" refers to that amount of a compound of the present invention which lowers IOP when administered to a patient, especially a mammal. The preferred route of

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administration is topical. The compounds of the present invention can be administered as solutions, suspensions, or emulsions (dispersions) in an ophthalmically acceptable vehicle. As used herein, the term "ophthalmically acceptable vehicle" refers to any substance or combination of substances which are non-reactive with the compounds and suitable for administration to a patient. Solubilizers and stabilizers are deemed to be non-reactive. Preferred are aqueous vehicles suitable for topical application to the patient's eyes.

In forming compositions for topical administration, the compounds of the present invention are generally formulated as between about 0.00003 to about 0.5 percent by weight (wt%) solutions in water at a pH between about 4.5 to about 8.0, preferably between about 5.0 and about 7.5. The compounds are preferably formulated as between about 0.0005 to about 0.03 wt% and, most preferably, between about 0.001 and about 0.01 wt%. While the precise regimen is left to the discretion of the clinician, it is recommended that the resulting solution be topically applied by placing one drop in each eye one or two times a day.

Other ingredients which may be desirable to use in the ophthalmic preparations of the present invention include preservatives, co-solvents, and viscosity building agents.

Antimicrobial Preservatives:

Ophthalmic products are typically packaged in multidose form. Preservatives are thus required to prevent microbial contamination during use. Suitable preservatives include: benzalkonium chloride, thimerosal, chlorobutanol, methyl paraben, propyl paraben, phenylethyl alcohol, edetate disodium, sorbic acid, Onamer M, or other agents known to those skilled in the art. Such preservatives are typically employed at a level between about 0.001% and about 1.0% by weight.

Co-Solvents:

Prostaglandins, and particularly ester derivatives, typically have limited solubility in water and therefore may require a surfactant or other appropriate co-solvent in the composition. Such co-solvents include: Polysorbate 20, 60 and 80; Pluronic F-68, F-84 and P-103; CREMOPHORE® EL (polyoxyl 35 castor oil); cyclodextrin; or other agents known to those skilled in the art. Such co-solvents are typically employed at a level between about 0.01% and about 2% by weight.

10 Viscosity Agents:

Viscosity greater than that of simple aqueous solutions may be desirable to increase ocular absorption of the active compound, to decrease variability in dispensing the formulations, to decrease physical separation of components of a suspension or emulsion of formulation and/or otherwise to improve the ophthalmic formulation. Such viscosity building agents include, for example, polyvinyl alcohol, polyvinyl pyrrolidone, methyl cellulose, hydroxy propyl methylcellulose, hydroxyethyl cellulose, carboxymethyl cellulose, hydroxy propyl cellulose, chondroitin sulfate and salts thereof, hyaluronic acid and salts thereof, and other agents known to those skilled in the art. Such agents are typically employed at a level between about 0.01% and about 2% by weight.

Preferred formulations of substituted tetrahydrofurans of the present invention include the following Examples 6-8:

Example 6

	Ingredient	Amount (wt %)
5	Compound VI	0.01
	Monobasic sodium phosphate	0.05
	Dibasic sodium phosphate (anhydrous)	0.15
	Sodium chloride	0.75
10	Disodium EDTA (Edetate disodium)	0.05
	Cremophor® EL	0.1
	Benzalkonium chloride	0.01
	HCl and/or NaOH	q.s. pH 7.3 - 7.4
15	Purified water	q.s. 100%

Example 7

	Ingredient	Amount (wt %)
5	Compound VII	0.003
	Sodium acetate (trihydrate)	0.07
	Mannitol	4.3
	Disodium EDTA (Edetate disodium)	0.1
	Cremophor® EL	0.5
10	Benzalkonium chloride	0.01
	HCl and/or NaOH	q.s. pH 5.0
	Purified water	q.s. 100%

15

Example 8

	Ingredient	Amount (wt %)
20	Compound VIII	0.05
	Phosphate Buffered Saline	1.0
	Hydroxypropyl- β -cyclodextrin	4.0
	Purified water	q.s. 100%

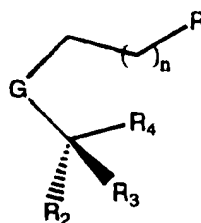
25

The invention has been described by reference to certain preferred embodiments; however, it should be understood that it may be embodied in other specific forms or variations thereof without departing from its spirit or essential characteristics. The

embodiments described above are therefore considered to be illustrative in all respects and not restrictive, the scope of the invention being indicated by the appended claims rather than by the foregoing description.

What is claimed is:

1. A method of treating glaucoma or ocular hypertension in a patient, which comprises administering to the patient a pharmaceutically effective amount of a compound of formula (III):



(III)

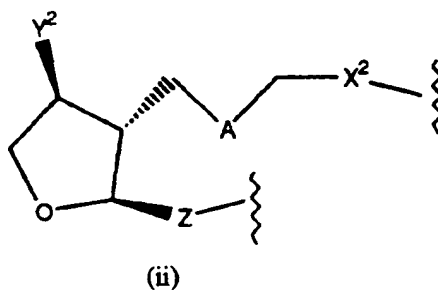
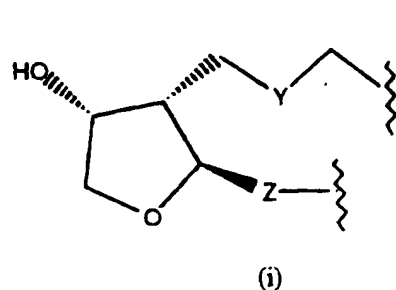
wherein:

R = ophthalmically acceptable ester moiety, CO_2R^1 , CONR^7R^8 , CH_2OR^9 , or $\text{CH}_2\text{NR}^{10}\text{R}^{11}$,

where $\text{R}^1 = \text{H}$ or cationic salt moiety; R^7 and R^8 are the same or different = H or alkyl; $\text{R}^9 = \text{H}$, acyl, or alkyl; R^{10} and R^{11} are the same or different = H, acyl, or alkyl; with the proviso that if one of R^{10} and $\text{R}^{11} = \text{acyl}$, then the other = H or alkyl;

$n = 0, 2$;

G is:



or

wherein:

$Y = \text{CH}_2\text{CH}=\text{CH}$ (*cis* olefin), $\text{CH}=\text{CHCH}_2$ (*cis* olefin), or $\text{CH}_2\text{CH}_2\text{CH}_2$;

$Z = \text{trans CH}=\text{CH}$ or CH_2CH_2 ; $\text{C}\equiv\text{C}$

$Y^2 = \text{halogen or alkoxy}$;

$X^2 = \text{O, S, or CH}_2$; and

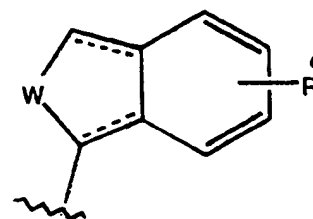
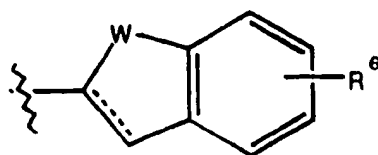
$A = \text{cis CH}=\text{CH}, \text{CH}_2\text{CH}_2, \text{ or } \text{C}\equiv\text{C}$;

one of R^2 and $R^3 = \text{H}$, and the other = F or OH, where the OH may be free or functionally modified; or R^2 and R^3 taken together = $\text{OCH}_2\text{CH}_2\text{O}$ or double bonded O (carbonyl); and

$R^4 = \text{cyclohexyl, linear or branched C}_3\text{-C}_7 \text{ alkyl, or } R^5$, wherein:

$R^5 = (\text{CH}_2)_m\text{Xphenyl or } (\text{CH}_2)_p Z^2$, where $X = \text{O or CH}_2$; $m = 1\text{-}6$; the phenyl is either unsubstituted or substituted with R^6 , where $R^6 = \text{halogen, CH}_3, \text{CF}_3, \text{CN, OCH}_3$, or acetyl; $p = 0\text{-}6$; and

$Z^2 =$



or

wherein:

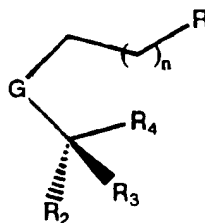
$W = \text{O, CH}_2, \text{CH}_2\text{CH}_2, \text{ or } \text{CH}=\text{CH}$; and R^6 is as defined above;

provided that when G is (i) then $R^4 = R^5$, and when G is (ii) then $R^4 = \text{cyclohexyl, linear or branched C}_3\text{-C}_7 \text{ alkyl, and } R^2, R^3 \text{ are different = H and OH.}$

2. The method of claim 1, where the compound is administered topically.

3. The method of claim 2, wherein the compound is administered as a solution, suspension, or emulsion.
4. The method of claim 2, wherein G is (i).
5. The method of claim 2, wherein G is (ii).
6. The method of claim 4, wherein R is an ophthalmically acceptable ester selected from the group consisting of: isopropyl and neopentyl esters of carboxylic acids.
7. The method of claim 5, wherein R is an ophthalmically acceptable ester selected from the group consisting of: isopropyl and neopentyl esters of carboxylic acids, and R⁴ is cyclohexyl.
8. The method of claim 3, wherein the concentration of the compound is between about 0.00003 to about 0.5 weight percent.
9. The method of claim 8, wherein the concentration of the compound is between about 0.0005 to about 0.03 weight percent.
10. The method of claim 9, wherein the concentration of the compound is between about 0.001 and about 0.01 weight percent.

11. A compound of formula (III):



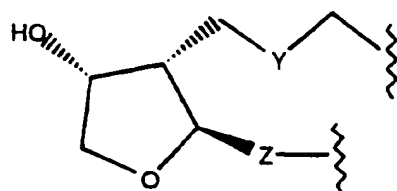
(III)

wherein:

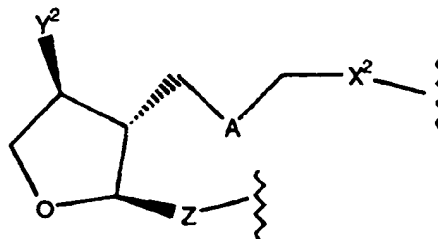
R = a pharmaceutically acceptable ester moiety, CO_2R^1 , CONR^7R^8 , CH_2OR^9 , or $\text{CH}_2\text{NR}^{10}\text{R}^{11}$, wherein $\text{R}^1 = \text{H}$ or cationic salt moiety; R^7 and R^8 are the same or different = H or alkyl; $\text{R}^9 = \text{H}$, acyl, or alkyl; R^{10} and R^{11} are the same or different = H, acyl, or alkyl; with the proviso that if one of R^{10} and $\text{R}^{11} = \text{acyl}$, then the other = H or alkyl;

$n = 0, 2$;

G is:



(i)



(ii)

or

wherein:

$\text{Y} = \text{CH}_2\text{CH}=\text{CH}$ (*cis* olefin), $\text{CH}=\text{CHCH}_2$ (*cis* olefin), or $\text{CH}_2\text{CH}_2\text{CH}_2$;

$\text{Z} = \text{trans CH}=\text{CH}$; CH_2CH_2 ; or $\text{C}\equiv\text{C}$;

$\text{Y}^2 = \text{halogen}$ or *alkoxy*;

$\text{X}^2 = \text{O}$, S , or CH_2 ; and

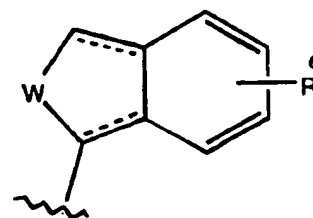
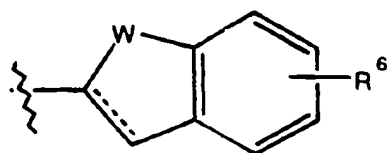
A = *cis* CH=CH, CH₂CH₂, or C≡C;

one of R² and R³ = H, and the other = F or OH, where the OH may be free or functionally modified; or R² and R³ taken together = OCH₂CH₂O or double bonded O (carbonyl); and

R⁴ = cyclohexyl, linear or branched C₅-C₇ alkyl or R⁵, wherein:

R⁵ = (CH₂)_mX phenyl, (CH₂)_pZ², where X = O or CH₂, m = 1-6; the phenyl is either unsubstituted or substituted with R⁶, where R⁶ = halogen, CH₃, CF₃, CN, OCH₃ or acetyl; p = 0-6; and

Z² =



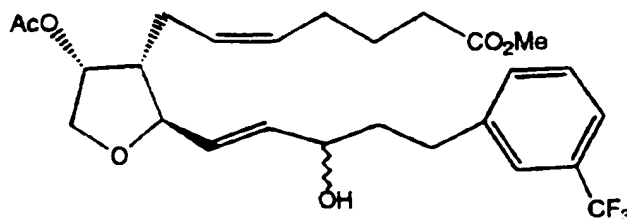
or

5 wherein:

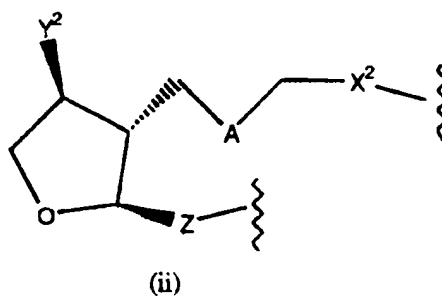
W = O, CH₂, CH₂CH₂, or CH=CH; and R⁶ is as defined above;

provided that when G is (i) then R⁴ = R⁵, and when G is (ii) then R⁴ = cyclohexyl, linear or branched C₅-C₇ alkyl, and R², R³ are different = H and OH;

with the proviso that the following compounds be excluded:



12. The compound of claim 11, where G is:



wherein:

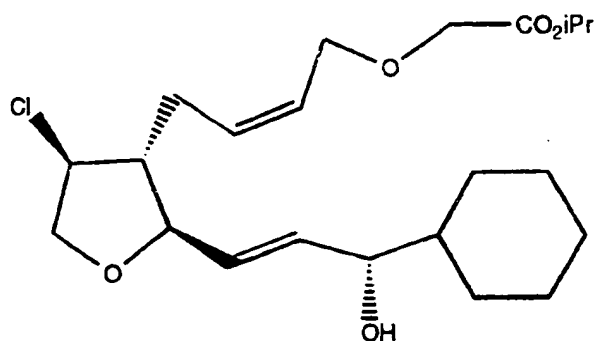
$Z = \text{trans CH=CH}$; CH_2CH_2 ; or $\text{C}\equiv\text{C}$;

$\text{Y}^2 = \text{halogen or alkoxy}$;

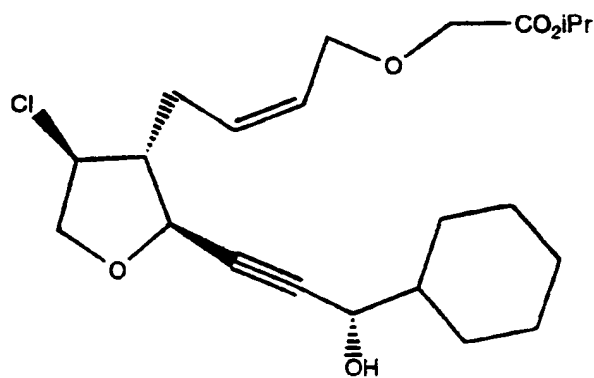
$\text{X}^2 = \text{O, S, or CH}_2$; and

$\text{A} = \text{cis CH=CH, CH}_2\text{CH}_2$, or $\text{C}\equiv\text{C}$.

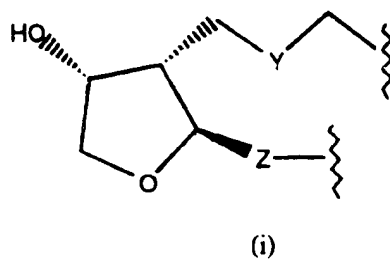
13. The compound of claim 12 having the following formula:



14. The compound of claim 12 having the following formula:



15. The compound of claim 11, where G is:

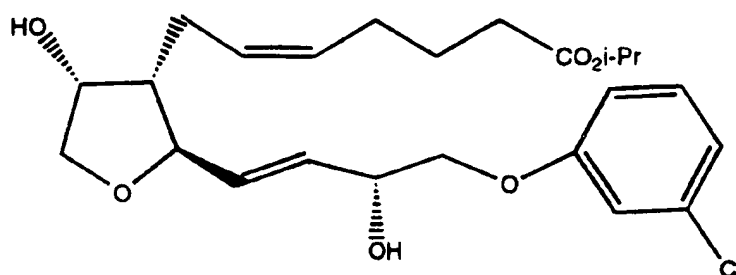


wherein:

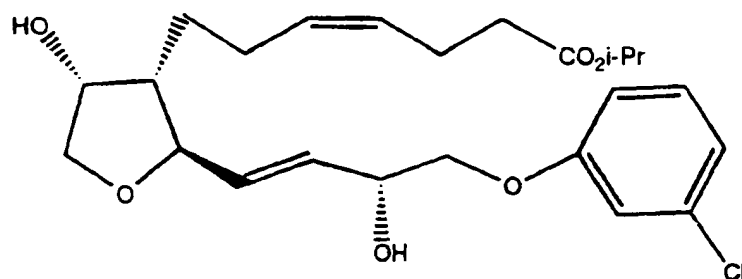
Y = $\text{CH}_2\text{CH}=\text{CH}$ (*cis* olefin), $\text{CH}=\text{CHCH}_2$ (*cis* olefin), or $\text{CH}_2\text{CH}_2\text{CH}_2$;

Z = *trans* $\text{CH}=\text{CH}$; CH_2CH_2 ; $\text{C}\equiv\text{C}$.

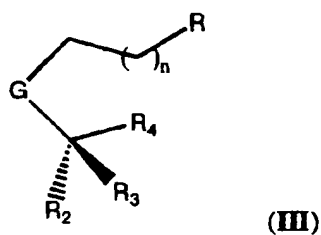
16. The compound of claim 15, having the following formula:



17. The compound of claim 15 having the following formula:



18. An ophthalmic composition for the treatment of glaucoma and ocular hypertension, comprising a compound of formula (III):



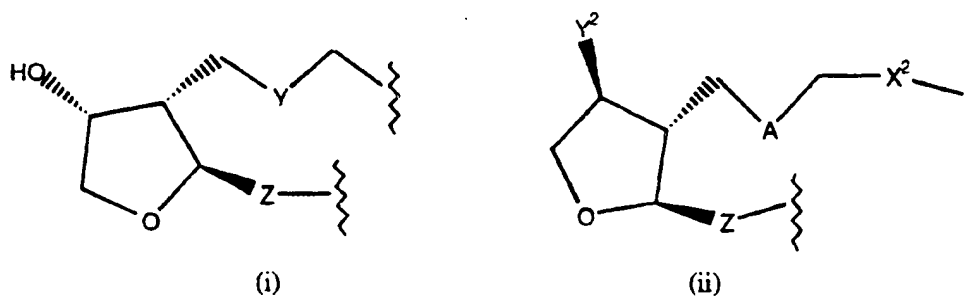
wherein:

R = ophthalmically acceptable ester moiety, CO₂R¹, CONR⁷R⁸, CH₂OR⁹, or CH₂NR¹⁰R¹¹.

where R¹ = H or cationic salt; R⁷ and R⁸ are the same or different = H or alkyl; R⁹ = H, acyl, or alkyl; R¹⁰ and R¹¹ are the same or different = H, acyl, or alkyl; with the proviso that if one of R¹⁰ and R¹¹ = acyl, then the other = H or alkyl;

n = 0, 2;

G is:



or

wherein:

Y = CH₂CH=CH (cis olefin), CH=CHCH₂ (cis olefin), or CH₂CH₂CH₂;

$$Z = \text{trans CH=CH} ; \text{CH}_2\text{CH}_2; \text{C}\equiv\text{C}:$$

Y² = halogen or alkoxy;

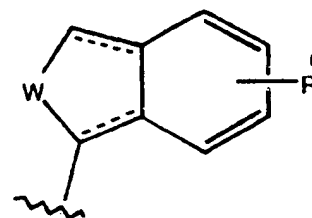
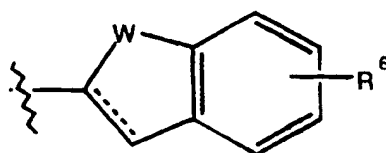
$X^2 = O, S,$ or CH_2 ; and

A = *cis* CH=CH, CH₂CH₂, or C≡C;

one of R^2 and $R^3 = H$, and the other = F or OH, where the OH may be free or functionally modified; or R^2 and R^3 taken together = OCH_2CH_2O or double bonded O (carbonyl); and

R⁴ = cyclohexyl, linear or branched C₅-C₇ alkyl, or R⁵, wherein:

$R^5 = (CH_2)_mXphenyl$ or $(CH_2)_pZ^2$, where $X = O$ or CH_2 ; $m = 1-6$; the phenyl is either unsubstituted or substituted with R^6 , where $R^6 = \text{halogen, } CH_3, CF_3, CN, OCH_3 \text{ or acetyl}$; $p = 0-6$; and

$$Z^2 =$$


OR

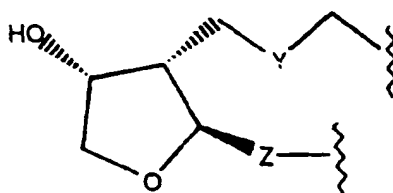
wherein:

$W = O, CH_2, CH_2CH_2$, or $CH=CH$; R^6 is as defined above:

provided that when G is (i) then $R^4 = R^5$, and when G is (ii) then $R^4 =$ cyclohexyl, linear or branched C_5-C_7 alkyl, and R^2, R^3 are different = H and OH:

and an ophthalmically acceptable vehicle therefor.

19. The composition of claim 18, where G is:



(i)

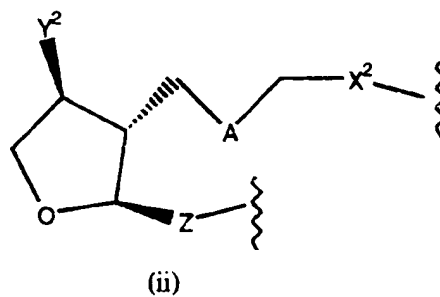
wherein:

$Y = CH_2CH=CH$ (*cis* olefin), $CH=CHCH_2$ (*cis* olefin), or $CH_2CH_2CH_2$; and

$Z = trans\ CH=CH$ or CH_2CH_2 ; $C\equiv C$;

and an ophthalmically acceptable vehicle therefor.

20. The composition of claim 18, wherein G is:



wherein:

Z = *trans* CH=CH or CH₂CH₂; C≡C;

Y² = halogen or alkoxy;

X² = O, S, or CH₂; and

A = *cis* CH=CH, CH₂CH₂, or C≡C;

and an ophthalmically acceptable vehicle therefor.

INTERNATIONAL SEARCH REPORT

International Application No
PC 96/17900

A. CLASSIFICATION OF SUBJECT MATTER

IPC 6 A61K31/557 C07D307/18 C07D307/20 C07D307/80 C07D407/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 A61K C07D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	S.AFRICAN J. CHEM., vol. 40, no. 2, 1987, pages 134-138, XP000618452 G.H.VERDOORN ET AL.: "Synthesis of methyl(5Z,13E)(15S)-9alpha-15-hydroxy-17-(3-trifluoromethylphenyl)-11-oxa-18,19,20-t rinorprosta-5,13-dienoate" cited in the application see the whole document ---	1-20
X	DE 24 60 977 A (KNOLL AG CHEMISCHE FABRIKEN) 1 July 1976 see the whole document ---	1-20
X	DE 26 01 333 A (CHEMBRO HOLDINGS (PROPRIETARY) LTD.) 22 July 1976 see page 5 ---	1-20
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *A* document member of the same patent family

Date of the actual completion of the international search

25 April 1997

Date of mailing of the international search report

2 3. 05. 97

Name and mailing address of the ISA

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Fax: (+ 31-70) 340-3016

Authorized officer

Theuns, H

INTERNATIONAL SEARCH REPORT

Application No
PCT/US 96/17900

C(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 26 18 861 A (CHEMBRO HOLDINGS (PROPRIETARY) LTD.) 11 November 1976 see the whole document ---	1-20
X	DE 27 39 277 A (PFIZER INC.) 16 March 1978 see the whole document ---	1-20
X	CARBOHYDRATE RES., vol. 141, no. 2, 1985, pages 221-238, XP000644751 S. HANESSIAN ET AL.: "TOTAL SYNTHESIS OF 11-OXAPROSTAGLANDIN F2alpha AND F2beta" see the whole document ---	1-20
X	S.AFR.J.CHEM., vol. 34, no. 4, 1981, pages 121-127, XP000618436 R.R.ARNDT ET AL.: "Stereospecific synthesis of modified prostaglandins derived from carbohydrates. Part 1. Stereocontrolled synthesis of 11-deoxy-11-oxaprostaglandin F2alpha methyl ester, 11-deoxy-11-oxaprostaglandin E2 methyl ester, and omega-chain modified analogues" ---	1-20
X	TETRAHEDRON LETTERS, no. 43, 1975, pages 3719-3722, XP000644760 G.J.LOURENS ET AL.: "THE NOVEL STEREOSPECIFIC SYNTHESIS OF 11-OXAPROSTAGLANDIN F2alpha" see the whole document ---	1-20
X	TETRAHEDRON LETTERS, no. 51/52, 1974, pages 4451-4454, XP000644759 I.VLATTAS ET AL.: "SYNTHESIS OF 11-OXAPROSTAGLANDINS" see the whole document ---	1-20
X	LIEBIGS ANN.CHEM., 1985, pages 2151-2164, XP000644761 J.THIEM ET AL.: "Synthese von Oxaprostaglandinen aus 1,4:3,6-Dianhydro-D-sorbit" see the whole document ---	1-20
1 A	WO 95 26729 A (PHARMACIA AB) 12 October 1995 ---	1
2 A	EP 0 686 628 A (ONO PHARMACEUTICAL CO., LTD.) 13 December 1995 ---	1
-/--		

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/US 96/17900

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>EP 0 667 160 A (ALCON LABIRATORIES, INC.) 16 August 1995</p> <p>-----</p>	1

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 96/ 17900

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☒ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
Remark: Although claim(s) 1-10
is(are) directed to a method of treatment of the human/animal
body, the search has been carried out and based on the alleged
effects of the compound/composition.
2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such
an extent that no meaningful International Search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all
searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment
of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report
covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is
restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/JP96/17900

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